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Yield potential and resource-use efficiency of maize systems in the western U.S. Corn Belt

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YIELD POTENTIAL AND RESOURCE-USE EFFICIENCY OF MAIZE SYSTEMS IN THE WESTERN U.S. CORN BELT

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Maize demand for food, livestock feed, and biofuel is expected to increase substantially. The Western U.S. Corn Belt accounts for 23% of U.S. maize production, and irrigated maize accounts for 43 and 58% of maize land area and total production, respectively, in this region. The most sensitive parameters (yield potential [Y_P], water-limited yield potential [$Y_{P\text{-}W}$], yield gap between actual yield and Y_P, and resource-use efficiency) governing performance of maize systems in the region are lacking. A simulation model was used to quantify Y_P under irrigated and rainfed conditions based on weather data, soil properties, and crop management at 18 locations. In a separate study, 5-year soil water data measured in central Nebraska were used to analyze soil water recharge during the non-growing season because soil water content at sowing is a critical component of water supply available for summer crops. On-farm data, including yield, irrigation, and nitrogen (N) rate for 777 field-years, was used to quantify size of yield gaps and evaluate resource-use efficiency. Simulated average Y_P and $Y_{P\text{-}W}$ were 14.4 and 8.3 Mg ha^{-1}, respectively. Geospatial variation of Y_P was associated with solar radiation and temperature during post-anthesis phase while variation in water-limited yield was linked to the longitudinal variation in seasonal rainfall and evaporative demand. Analysis of soil water recharge indicates that 80% of variation in soil water content at sowing can be explained by precipitation during non-growing season and residual soil water at end of previous growing season. A linear relationship between Y_{P-W} and water supply (slope: 19.3 kg ha^{-1} mm^{-1}; *x*-intercept: 100 mm) can be used as a benchmark to diagnose and improve farmer's water productivity (WP; kg grain per unit of water supply). Evaluation of data from farmer's fields provides proof-of-concept and helps identify management constraints to high levels of productivity and resource-use efficiency. On average, actual yields of irrigated maize systems were 11% below Y_P. WP and N-fertilizer use efficiency (NUE) were high despite application of large amounts of irrigation water and N fertilizer (14 kg grain mm^{-1} water supply and 71 kg grain kg^{-1} N fertilizer). While there is limited scope for substantial increases in actual average yields, WP and NUE can be further increased by: (1) switching surface to pivot systems, (2) using conservation instead of conventional tillage systems in soybean-maize rotations, (3) implementation of irrigation schedules based on crop water requirements, and (4) better N fertilizer management.

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CHAPTER 1: CONCEPTUAL FRAMEWORK TO BENCHMARK ACTUAL PRODUCTIVITY AND RESOURCE-USE EFFICIENCY IN CROPPING SYSTEMS

1.1. Production levels

Production ecology studies the integration of basic information on physical, chemical, physiological, and ecological processes to elucidate the performance of cropping systems (Loomis and Connor, 1992; van Ittersum and Rabbinge, 1997). Production levels are defined according to the growth limitations imposed by genotype, climate, and abiotic and biotic stresses. The production-level framework can be used to investigate the relative importance of necessary growth factors and inputs to explain actual yield levels and to analyze differences between potential and actual yields levels as the basis for identifying potential improvements in crop and soil management.

Yield potential (Y_P) is defined as the yield of a crop cultivar when grown in an environment where water and nutrients are non-limiting and biotic stresses are effectively controlled (Evans, 1993; van Ittersum and Rabbinge, 1997; Cassman *et al.*, 2003) (Fig. 1-1). Thus, Y_P is determined by weather variables (mainly solar radiation and temperature) and by genotype-specific physiology and phenology. Y_P varies across locations and years as a result of the normal variation in solar radiation and temperature. When water is limiting, water-limited yield potential (Y_{P-W}) is determined by solar radiation, temperature, and water supply amount and distribution (Cassman *et al.*, 2003; Passioura *et al.*, 2007). Water supply includes stored available soil water at sowing, sowing-to-maturity rainfall, and water applied with irrigation. Inclusion of *all* components of the water supply budget is critical to determine the degree of limitation by water and to estimate the yield gap between a farmer's yield and $Y_{P\text{-}W}$ (see Section 1.3).

Farmers influence Y_P and $Y_{P\text{-}W}$ via management tactics such as sowing date, cultivar maturity, target plant population density, and row spacing (Lobell *et al.*, 2009). Thus, not site-specific climate, but also management practices define average Y_P for a particular location. Y_P based on average management practices used by farmers is typically below (~ 10-20%) maximum Y_P obtained using the best combination of management practices ('perfect management') (Fig. 1-1) because farmers seek to maximize profit, within an acceptable risk level, rather than yield, and therefore utilize cost-effective practices that may not maximize yield (Cassman *et al.*, 2003; Keating *et al.*, 2010). There is, however, a trade-off associated with using sub-optimal input levels: while risk is diminished, actual yields may be limited in years in which weather conditions would allow higher Y_P or attainable water-limited yields (Sadras, 2002). In rainfed systems, for example, farmers adopt conservative cropping strategies that are adjusted to average water availability. Whereas this approach stabilizes the typically low and highly variable yields and reduces economic risk, it also limits yields in seasons with optimum rainfall.

Actual yields, *i.e.*, the yields achieved by farmers, are typically well below Y_P (or $Y_{P\text{-}W}$ in cropping systems where water supply is limiting) due to inadequate supply of, or imbalances among, any of the 17 essential nutrients for crop growth, as well as due to incidence of biotic (*e.g.*, weeds, insect pests, and diseases) and abiotic yield-reducing factors (*e.g.*, hail, lodging, and frost) (Fig. 1-1). The difference between average Y_P (or attainable water-limited yield when water is limiting) and actual yields represent the exploitable yield gap. Lobell *et al.* (2009) summarized estimates of yield gap magnitudes reported for major rainfed and irrigated cropping systems. They found a wide range of yield gaps, with average actual yields ranging from 20 to 80% of Y_P or $Y_{P\text{-}W}$. While rainfed crops exhibit large yield gaps (> 50% of $Y_{P\text{-}W}$), considerably smaller gaps were found in reported values for major irrigated cropping systems (20-30% of Y_P).

1.2. Yield-gap analysis

Steady increase in food production over the last 30 years was sustained by higher productivity per unit area of land as cereal area has remained stable, or even decreased, due to limiting arable land reserves and increasing demand for land for residential and recreational uses (Cassman *et al.*, 2003). The lack of increase in Y_P during the same time period suggests that increasing productivity per unit area of land occurred at expense of reducing the size of the gap between Y_P and farmer's yields (Bell *et al.*, 1995; Duvick and Cassman, 1999; Peng *et al.*, 1999). Further increases in farmer's yields are required to ensure future food security and prevent conversion of biodiversity-rich ecosystems into agricultural land and consequent loss of ecological services and increase in greenhouse gas emissions (Tilman *et al.*, 2002; Cassman *et al.*, 2010). However, as actual yields approach Y_P, it becomes more difficult for farmers to sustain yield increases because further gains require the elimination of small imperfections in the management of the cropping system which are usually not economically viable (Cassman *et al.*, 2003). For example, yield plateaus have been detected for cropping systems where average farmer's yields approached 70-80% of Y_P for rice in China and wheat in north-western Europe (Lobell *et al.*, 2009; Cassman *et al.*, 2010) (Fig. 1-2). Hence, analysis of the gap between actual yield and Y_P serves as a tool not only to diagnose current productivity, but also to predict the likelihood of future yield increase in a particular cropping system.

Reliable estimates of average Y_P (or $Y_{P\text{-}W}$ when water is limiting) are required for performing yield-gap analysis. Lobell *et al.* (2009) provides a critical summary of different approaches used to estimate Y_P. Although yields from field experiments and sanctioned yield contests can be used as a measure of Y_P, such estimates are subject to several sources of error: (i) there is a high level of uncertainty in ensuring that all limiting factors were effectively removed because achieving perfect management is very difficult, even in fields managed to minimize constraints; (ii) management practices employed in these trials may not represent average management practices used by farmers; and (iii) measured Y_P in single or even several years and locations may not fully account for year-to-year and geospatial variation in weather (Bell *et al.*, 1995; Cassman and Duvick, 1999; Evans and Fischer, 1999). Another approach to estimate Y_P relies on theoretical estimates based on maximum physiological efficiencies (Loomis and Williams, 1963; Tollenaar, 1983), later embedded into crop simulation models (Muchow *et al.*, 1990; Yang *et al.*, 2004). These models provide a robust approach to estimate Y_P for a particular cropping system so long as model performance has been previously validated against independent field data and simulations are based on actual daily weather data, soil properties, and farmer's average crop management, including sowing date, crop maturity, and plant population density.

1.3. Resource-use efficiency

A complete assessment of cropping-system performance requires analyzing both production levels and resource-use efficiency (van Ittersum and Rabbinge, 1998). From a production ecology perspective, resource-use efficiency is defined as the amount of economic yield per unit of input. Economic yield is the desired plant product, which can be grain, oilseed, tubers, corms, sugar, fiber, forage, or energy depending on the crop in question. Typical inputs to cropping systems include labor, fossil-fuel, water, nutrients, and pesticides. The present research is focused on water and nitrogen (N) which are two of the most typical limiting factors in existing cropping systems.

The benchmark concept is useful to diagnose water productivity (~ water-use efficiency; kg grain per unit of water supply) in agricultural systems (Fig. 1-3a). Typically, yield is plotted against water supply and a function delimiting $Y_{P\text{-}W}$ over the range of water supply is used as a benchmark to diagnose water productivity (*e.g.*, French and Schultz, 1984; Passioura, 2007; Passioura and Angus, 2010). On-farm yield and water supply data can be compared against the benchmark to estimate actual water productivity: for a particular farm, the greater the distance to the benchmark, the lower the water productivity. The benchmark approach requires accounting for all components of the water supply budget as their relative contribution may vary across years, regions, and management tactics. For example, consider two years in a rainfed cropping system with the same amount and distribution of rainfall during growing season but different soil water content at sowing: 'low' (year 1) and 'high' soil water (year 2) (Fig. 1-3b). $Y_{P\text{-}W}$ increases from year 1 to 2 as a result of higher initial soil water content (points 1A to 2A). Assuming the same actual yield in both years (points 1B and 2B), the efficiency in the use of the water supply to produce grain yield ('water productivity') is higher in year

1 compared to year 2. However, if initial soil water content is not accounted for in calculation of total water supply, apparent $Y_{P\text{-}W}$ is the same for both years (point 1A) whereas water productivity is grossly overestimated in year 2 (segments 1A-B *versus* 2A-B).

In a classic study, de Witt (1992) stated that production resources are used more efficiently when they are all at their optimum level. Accordingly, high yield levels are related to high resource-use efficiencies due to optimization of growing conditions. Paradoxically, resource-use efficiency in high-yield cropping systems is often perceived to be intrinsically low due to large inputs applications (*e.g.*, N fertilizer, irrigation water) and associated environmental degradation (Addiscott *et al.*, 1991; Pretty *et al.*, 2000; Keating *et al.*, 2010). There are, however, well-managed field-scale experiments that document the potential to achieve both high yields with high resource-use efficiency with precise management of all production factors in time and space (Cassman, 1999; Dobermann *et al.*, 2002; Verma *et al.*, 2005). Trends towards higher yield levels with higher resource-use efficiency also have been reported for some intensive cropping systems as a result of better crop and inputs management (Cassman *et al.*., 2002). Since intensive cropping systems account for a significant fraction of total cereal production, identification of avenues for improvement of resource-use efficiency without yield penalties is critical to guarantee global food security and preserve natural resources for future generations.

1.4. Research justification

Justification for this research and main features about maize systems in the Western U.S. Corn Belt are presented in detail elsewhere (Chapters 2, 3, 4, and 5). Briefly, the Western U.S. Corn Belt (37ºN-45ºN; 92ºW-105ºW) includes one of the largest areas cultivated with maize in the world (7.3 million ha) mostly located in Kansas, Nebraska, and South Dakota (USDA-NASS, 2003-2007). Irrigated maize represents 43% of the total maize area and accounts for 58% of the total annual maize production of 60 million Mg in this region.

Duvick and Cassman (1999) reported Nebraska state-level yield to be approximately 50% below the Y_P estimated from reported contest-winning yield levels (18.2 Mg ha^{-1}). Average Y_P may be smaller than contest-winning yields because winning yields come from the most favourable genotype x environment interaction over a large geographic area. Hence, neither Y_P nor the magnitude of the exploitable yield gap has been accurately quantified in maize systems in the Western U.S. Corn Belt.

Despite claims about low resource-use efficiency on intensive cropping systems (see previous section), there has been no thorough assessment of the actual water productivity and nitrogen-use efficiency in farmer's fields in the U.S. Corn Belt. Likewise, despite the large number of reported yield/water supply relationships reported for maize (see Appendix), explicit attempts to develop an analytical framework for analysis and improvement of on-farm water productivity are not found in the literature.

Variation in the initial soil water has an impact on subsequent yields of rainfed crop production (Neild *et al.*, 1987). In irrigated crop production, knowledge of initial soil water status can help with irrigation scheduling. Estimates of soil water content at sowing would also be useful for crop consultants and farmers to support management decisions such as plant population, hybrid-maturity, and nutrient application (Lyon *et al.*, 2003). However, there are no published methods for estimating soil water recharge during the non-growing season, which would allow estimation of soil water content at the beginning of the summer-crop growing season in the Western U.S. Corn Belt.

1.5. Research goals

The main goal of the present research is to evaluate the performance of maize systems in the Western U.S. Corn Belt based on the quantification of key parameters including Y_P, $Y_{P\text{-}W}$, exploitable yield gap, and resource-use efficiency. This dissertation begins with a simulation analysis which aims to identify the most sensitive factors accounting for variations in maize Y_P and $Y_{P\text{-}W}$ (Chapter 2). After that, the dissertation presents an analysis of soil water recharge during the non-growing season which determines the stored soil water at the beginning of summer-crop growing season, which is a critical component of the total water supply available for maize crops (Chapter 3). Based on the complementary use of on-farm data, simulation modeling, and geospatial tools, the study focuses then on the diagnosis and improvement of yield levels and resource-use efficiency (with emphasis on water and N) in existing high-yield irrigated maize systems (Chapters 4 and 5). A major objective of the present research project was the development of a benchmark for water productivity that can be used to diagnose cropping-system performance. Finally, Chapter 6 summarizes the main findings of this research and associated implications and questions that arose from this research. Chapter 6 also includes a comparison between intensive cropping systems (maize in the U.S. Corn

Belt and rice in the Philippines) and low-input cropping systems (wheat in Australia and sunflower in Argentina) in terms of production level, resource inputs, and resource-use efficiency.

To summarize, the main objectives of the present research are:

- to quantify maize Y_P, water-limited Y_P, and their association with meteorological variables in the Western U.S. Corn Belt (Chapter 2);
- to derive algorithms to estimate soil water content at the beginning of the summer-crop growing season (Chapter 3);
- to diagnose yield gaps and resource-use efficiency (with emphasis on water and N) in actual irrigated maize systems (Chapters 4 and 5);
- to develop a framework to evaluate on-farm water productivity (Chapter 5);
- to identify opportunities for increasing actual yields, WP, and NUE (Chapters 4 and 5).

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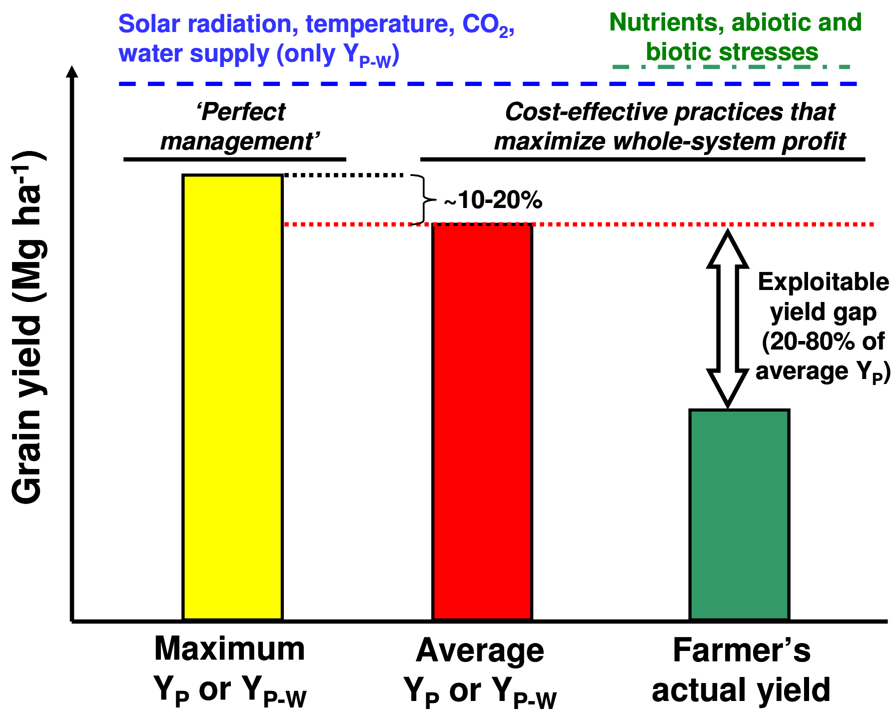

Figure 1-1. Schematic relationship between production levels (maximum and average yield potential [Y_P] or water-limited yield potential [$Y_{P\text{-}W}$] and actual farmer's yield) and weather and management factors. Adapted from van Ittersum and Rabbinge (1997), Cassman *et al.* (2003), and Lobell *et al.* (2009).

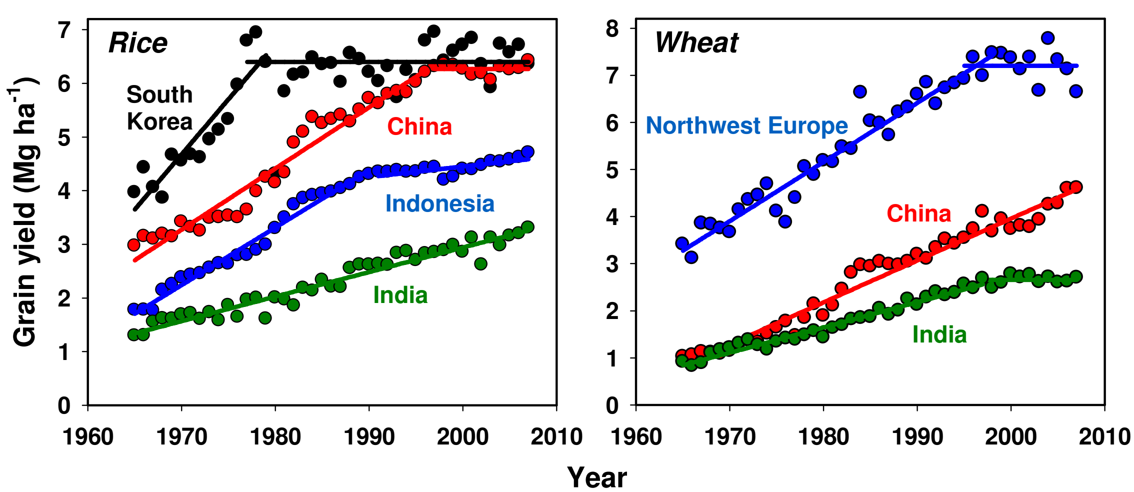

Figure 1-2. Grain yield trends of rice and wheat in selected countries. Data source: FAOSTAT. Modified from *Cassman et al.* (2010).

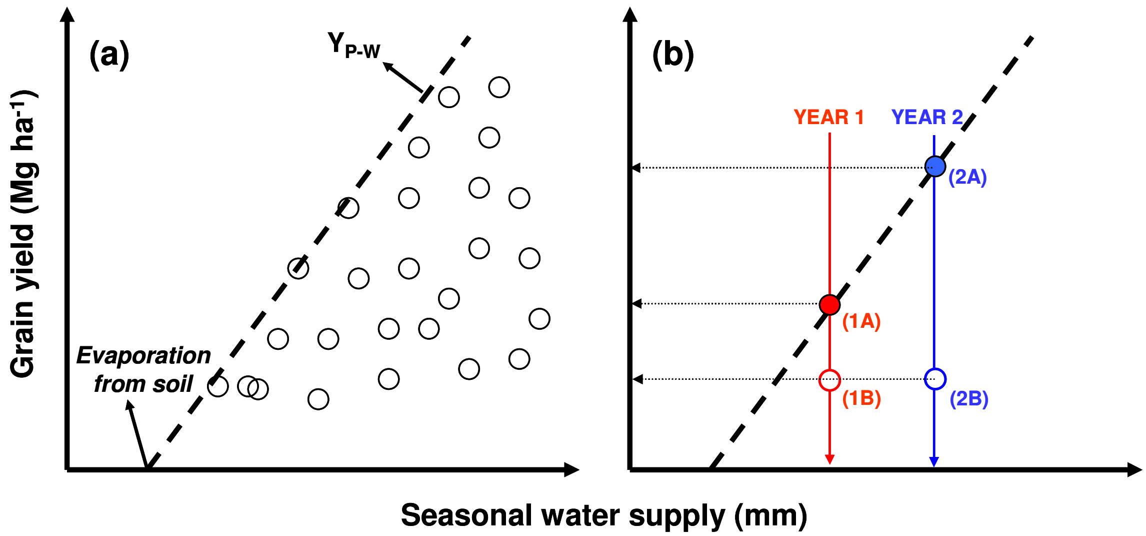

Figure 1-3. (a) Schematic relationship between yield and seasonal water supply (stored soil water at sowing plus sowing-to-maturity rainfall and applied irrigation). Dashed line delimits water-limited yield potential (Y_{P-W}); the x-intercept is a rough estimate of seasonal soil evaporation. Circles represent farmer's yields which are typically below the dashed line due to constraints from nutrition deficiencies or inadequate control of diseases, insect pests, and weeds. Adapted from French and Schultz (1984) and Passioura (2002). (b) Example of bias caused when soil water content at sowing is not accounted for in calculation of seasonal water supply. Solid and empty circles indicate Y_{P-W} and actual yields, respectively, in two years with same amount and distribution of rainfall and similar temperatures and solar radiation, but contrasting initial soil water contents: 'low' (year 1) and 'high' (year 2) soil water.

CHAPTER 2: LIMITS TO MAIZE PRODUCTIVITY IN WESTERN CORN BELT: A SIMULATION ANALYSIS FOR FULLY-IRRIGATED AND RAINFED CONDITIONS [1]

ABSTRACT

Unlike the Central and Eastern U.S. Corn Belt where maize is grown almost entirely under rainfed conditions, maize in the Western Corn Belt is produced under both irrigated (3.2 million ha) and rainfed maize (4.1 million ha) conditions. Simulation modelling, regression, and boundary-function analysis were used to assess constraints to maize productivity in the Western Corn Belt. Aboveground biomass, grain yield, and water balance were simulated for fully-irrigated and rainfed crops, using 20-year weather records from 18 locations in combination with actual soil, planting date, plant population, and hybrid-maturity data. Daily mean temperature and cumulative solar radiation were estimated for three growth periods (pre- and post-silking, and the entire growing season) and used to identify major geospatial gradients. Linear and stepwise multiple regressions were performed to evaluate variation of potential productivity in relation to meteorological factors. Boundary functions for the relationship between productivity and seasonal water supply or crop evapotranspiration were derived and compared against observed data reported in the literature. Geospatial gradients of seasonal radiation, temperature, rainfall, and evaporative demand along the Western Corn Belt were identified. Yield potential with irrigation did not exhibit any geospatial pattern,

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depending instead on the specific radiation / temperature regime at each location and its interaction with crop phenology. A linear and parabolic response to post-silking cumulative solar radiation and mean temperature, respectively, explained variations on yield potential. Water-limited productivity followed the longitudinal gradient in seasonal rainfall and evaporative demand. Rainfed crops grown in the Western Corn Belt are frequently subjected to episodes of transient and unavoidable water stress, especially around and after silking. Soil water at sowing ameliorates, but does not eliminate water stress episodes. Boundary functions for the relationship between aboveground biomass and grain yield versus seasonal water supply had slopes of 46 and 28 kg ha^{-1} mm^{-1}. At high seasonal water supply, productivity was weakly correlated with water supply because many crops did not fully utilize seasonally available water due to percolation below the root zone or water left in the ground at physiological maturity. Fitted boundary functions for the relationships between aboveground biomass and grain yield versus crop evapotranspiration had slopes (≈ seasonal transpiration-efficiency) of 54 and 37 kg ha^{-1} mm^{-1}, respectively, and an x-intercept around 25-75 mm (≈ seasonal soil evaporation). Data collected from experiments conducted in low-rainfall environments indicated that the boundary functions for water-use efficiency, derived from this study, are broadly applicable.

Keywords: maize, Zea mays L., yield potential, water-limited yield, simulation model, rainfall shortage, water productivity

Abbreviations: ASW_S: available soil water at sowing (mm); ET_C: crop evapotranspiration (mm); ET_O: reference evapotranspiration (mm,); FRP: fully-recharged soil profile; PRP: partially-recharged soil profile; TE_S: seasonal crop transpiration efficiency (kg mm^{-1} ha^{-1}); T_{mean}, T_{max}, and T_{min}: daily mean, maximum, and minimum temperature (ºC); WSI: water-stress index; Y_P: yield potential.

2.1. INTRODUCTION

Yield potential (Y_P) is defined as the yield of a crop cultivar when grown in an environment to which it is adapted, with nutrient and water non-limiting and pests and diseases effectively controlled (Evans, 1993). Hence, Y_P for a given genotype is determined by the particular combination of solar radiation, temperature and plant population at a specific location (van Ittersum and Rabbinge, 1997). Y_P can be diminished as a consequence of insufficient water supply to meet crop water demand. Thus, water-limited yield is determined by the genotype, solar radiation, temperature, plant population and the degree of water limitation (Loomis and Connor, 1992). Insufficient water supply can result from sub-optimal seasonal water supply (stored soil water plus growing-season rainfall) in rainfed systems or sub-optimal irrigation in irrigated systems. Accurate quantification of Y_P and water-limited limited yield is essential to estimate the magnitude of the exploitable gap between actual (*i.e.*, those achieved by farmers) and attainable yields, to predict global change scenarios, and to help formulate policies to ensure local and global food security (Cassman *et al.*, 2003). The lack of data from experiments in which yield-limiting factors have been effectively controlled makes it difficult to obtain reliable quantifications of Y_P and water-limited yield based on actual measurements (Duvick and Cassman, 1999). When such data are lacking, simulation models can provide reasonable estimates of Y_P and water-limited yields when soil and historical daily weather data are available, including solar radiation, daily temperature, and rainfall (*e.g.*, Amir and Sinclair, 1991a, b; Yang *et al.*, 2004).

Although maize production must increase substantially to meet the rapidly increasing demand for food, livestock feed, and biofuel at a global scale (Cassman *et al.*, 2003; Cassman and Liska, 2007), there has been little increase in maize Y_P in the last 30 years (Duvick and Cassman, 1999; Tollenaar and Lee, 2002). Studies attempting to understand maize yield potential and its variation in relation to environmental factors have highlighted the crucial role of solar radiation and temperature (Muchow *et al.*, 1989; Cirilo and Andrade, 1994; Otegui *et al.*, 1995, 1996). A few studies have attempted to quantify Y_P and its variation at a regional scale using observed data (Duncan *et al.*, 1973; Andrade *et al.*, 1996) and simulation modelling (Hodges *et al.*, 1987; Muchow *et al.*, 1990; Löffler *et al.*, 2005; Wilson *et al.*, 1995). In all of these studies, maize yields were evaluated against mean values of meteorological variables calculated for the entire growing season rather than specific growth phases that are most sensitive to environmental limitations (Otegui and Bonhomme, 1998). Likewise, it was not clear if the management practices used at all locations were optimal for maximum attainable yield. As a result, measured or simulated yields appear to be well below maize Y_P. Finally, simulation models such as CERES-Maize (Jones and Kiniry, 1986) and the Muchow-Sinclair-Bennett model (Muchow *et al.*, 1990) do not account explicitly for direct effects of temperature on gross carbon assimilation and respiration, which may have a significant impact on yield estimates in cool or warm environments (*e.g.*, Edmeades and Bolaños, 2001).

Water resources for agriculture are heavily exploited and there is increasing competition for limited water supplies in most countries with extensive irrigated agriculture (Rosegrant *et al.*, 2002). Therefore, quantifying the maximum yield per unit of available water supply, hereafter called the water-limited yield, is essential for identifying water management practices and policies to optimize water-use efficiency (Wallace, 2000). Boundary functions provide a robust framework to analyze water-limited productivity (*e.g.*, French and Schultz, 1984; Passioura, 2006; Sadras and Angus, 2006). Yield is plotted against either: (i) water supply (stored soil water at sowing plus rainfall), or (ii) crop evapotranspiration (ET_C), on a seasonal basis, and a linear function is fitted to those data that delimit the upper frontier for yield. The first approach provides a benchmark to help farmers set target yields and identify other yield reducing-factors, such as nutrients, pests, and diseases (Passioura, 2006). The second approach based on ET_C provides a physiological frontier for water-limited productivity in which the slope represents the seasonal transpiration-efficiency (TE_S) and the *x*-intercept gives a rough estimate of seasonal soil evaporation (Sinclair *et al.*, 1984). Despite the large number of reported yield/water supply relationships reported for maize, we were not able to find any explicit attempt to define maximum boundary functions for water-use efficiency.

To fill this knowledge gap about maize productivity and its variability, we used a crop simulation model (Yang *et al.*, 2004), regression and boundary function analysis to assess limits to maize aboveground biomass and grain yield in the Western Corn Belt. The primary objectives of this work were to: (i) identify geospatial patterns of radiation, temperature, rainfall, reference evapotranspiration, and water-stress; (ii) explain geospatial variations in Y_P in relation to these climate variables; and (iii) determine boundary functions for the relationships between grain yield or aboveground biomass and seasonal water supply or ET_C.

2.2. MATERIAL AND METHODS

2.2.1. The Western Corn Belt

The Western U.S. Corn Belt (37ºN-45ºN; 92ºW-105ºW) includes about 7.3 million ha cultivated with maize, mostly located in Kansas, Nebraska, and South Dakota (Fig. 2-1) (USDA-NASS, 2003-2007). Irrigated maize represents 43% of the total maize area (70% of the total irrigated cropland in the region) and accounts for 58% of the total annual maize production of 60 million Mg in the Western Corn Belt. On-farm yields range from 2.4 to 8.1 Mg ha^{-1} under rainfed conditions, and from 8 to 11.2 Mg ha^{-1} with irrigation. These values are well below the highest reported yields for rainfed (6.7-13.5 Mg ha^{-1}) and irrigated maize (13.3-18.4 Mg ha^{-1}) in the region (Duvick and Cassman, 1999).

Soil and climate in the region are described by Smika (1992). The landscape is undulate. Predominant agricultural soils are Haplustolls and Argiustolls with medium-to-high water holding capacity. Elevation increases by 118 m per longitude degree, from east to west (range: 309 m in Ames, IA to 1384 m in Akron, CO). The climate is continental and temperate, and the frost-free period decreases from the southeast to the northwest along the altitudinal gradient. Annual rainfall decreases from east to west, and its distribution follows a monsoonal pattern: 70-80% of the precipitation is concentrated in the spring and summer seasons. Evaporative demand exceeds rainfall during the summer growing-season such that most rainfed crops depend on stored soil moisture that accumulates from snow melt and spring rains (Loomis and Connor, 1992).

2.2.2. Model evaluation

Hybrid-Maize (Yang *et al.*, 2004, 2006) is a process-oriented model that simulates maize development and growth on a daily time step under growth conditions without limitations from nutrient deficiencies or toxicities, or from insect pests, diseases, or weeds. It features temperature-driven maize development, vertical canopy integration of photosynthesis, organ-specific growth respiration, and temperature-sensitive maintenance respiration. Simulation of photosynthesis, growth respiration and maintenance respiration makes the Hybrid-Maize model more responsive to changes in environmental conditions than models such as CERES-Maize or the Muchow-Sinclair-Bennett model, which utilize radiation-use efficiency (RUE) to integrate the processes of assimilation and respiration. The results presented here extend the original model validation reported by Yang *et al.* (2004).

Maize yields were obtained from field studies conducted over 43 site-years that including rainfed (n = 13) and fully-irrigated (n = 30) field studies (Table 2-1). The database did not include fields with obvious limitations due to nutrient deficiencies, diseases, insects, weeds, hail or waterlogging. Simulated grain yields were compared against observed values and root mean squared error (RMSE) was calculated. For rainfed crops, available soil water at sowing (ASW_S) was estimated based on rainfall during the period from October to the planting date at each site, soil water holding capacity, and simulated ASW left in the ground by the previous maize crop (data not shown). Temperature and radiation data were obtained from the nearest meteorological station, which, on average, was located ≈ 14 km away from each field (range: 0-40 km). Rainfall was recorded at the field study site in 75% of the site-years or at the nearest meteorological station. Simulations were based on the actual soil texture, planting date, plant population, and hybrid used at each site. Grain yields for this model evaluation, and for all other simulations in this paper, are reported at a standard moisture content of 0.155 kg H_2O kg^{-1} grain.

2.2.3. Simulated yield and water balance

Rainfed and irrigated yield were simulated at 18 sites across the Western Corn Belt (Fig. 2-1). Grain yield, aboveground biomass on an oven-dry basis, and water balance components [soil evaporation, crop evapotranspiration (ET_C), percolation below root zone, and residual ASW at maturity] were simulated using long-term (20-year) weather records. Simulations utilized the actual soil type, average sowing date, and the recommended hybrid-maturity for each site (Table 2-2). Average sowing date was the date when 50% of the total maize area was planted according to 2004-2006 county-level report on planting progression obtained from the Risk Management Agency-USDA (Rebecca Davis, personal communication). The predominant soil series suitable for maize production was identified in an area of 710 km^2 around each meteorological station using STATSGO (USDA, 1994) and SSURGO (USDA, 1995) databases, and the soil texture of that soil series, derived from the official soil series descriptions (USDA-NRCS), was specified in the rainfed simulations because soil water retention and release characteristics are based on soil texture in Hybrid-Maize. None of these soils have physical impediments to root growth and so root depth was set at 1.5 m, based on soil water extraction patterns reported by Payero *et al.* (2006).

The recommended plant population and hybrid-maturity for each location were provided by agronomists from a major seed company. A fixed plant population (80,000 plants ha^{-1}) was set for irrigated crops because recommended population did not vary across locations with irrigation. In contrast, recommended plant populations varied from 32,000 to 78,000 plants ha^{-1} along the west-east gradient of increasing rainfall (Table 2-2, Fig. 2-2). Site-years in which minimum temperature fell below freezing during grain-filling were not allowed to exceed 25% of the 20-year simulation period (Table 2-2). Simulations ended at physiological maturity for the recommended hybrid at each site. Two ASW_S scenarios were simulated for rainfed crops: fully-recharged profile (FRP, whole profile at 100% ASW) and partially-recharged profile (PRP; upper 0.3 m at 100% ASW, rest of the profile at 25% ASW). The scenarios are representative of the expected range in ASW_S, based on: (i) 3-year ASW data at 8 locations between 97ºW-104ºW along the east-west rainfall gradient (data provided by the High-Plains Regional Climate Center), (ii) 20-year water balance computations during the fallow's period, and (iii) our expert opinion.

2.2.4. Geospatial patterns of meteorological variables and productivity

For each site-year simulation, mean values for the following meteorological variables were estimated: daily and cumulative incident solar radiation, daily maximum (T_{max}), mean (T_{mean}) and minimum temperature (T_{min}), daily relative humidity, cumulative rainfall, and cumulative ET_O (estimated using Penman's equation). Mean values for the previous meteorological variables were calculated for the entire crop cycle (*i.e.*, from sowing to physiological maturity), the pre-silking (*i.e.*, from sowing to silking), and post-silking (*i.e.*, from silking to physiological maturity) phases. 20-year mean values at each location were then plotted against latitude and longitude to identify major geospatial gradients. Linear or second-order polynomial functions were fitted. A similar analysis was performed to identify geospatial patterns in potential and rainfed aboveground biomass and grain yield.

2.2.5. Growing-season rainfall, evaporative demand, and water stress patterns

Hybrid Maize was used to describe seasonal rainfall, crop water use, and water stress patterns of rainfed maize based on 20 years of weather data at Akron, CO and Mead, NE, which are representative of the longitudinal gradients of rainfall and ET_O in the Western Corn Belt (Fig. 2-1). Model inputs for each site are shown in Table 2-2. The crop growth period, from emergence to physiological maturity, was divided into 20-day intervals. For each interval, mean and tercile values were calculated for cumulative rainfall, cumulative maximum ET_C (*i.e.*, the ET_C a crop would have when grown under non-water limiting conditions), and average water-stress index (WSI). Hybrid-maize simulates maximum ET_C as a function of the evaporative demand and leaf area. WSI is calculated as: 1 -

actual transpiration / potential transpiration (range: 0 [no stress] to 1 [maximum stress], see Yang *et al.*, 2006). WSI patterns were simulated for the two ASW_S scenarios (FRP and PRP initial soil water).

2.2.6. Explanation of geospatial variation in aboveground biomass and grain yield

Pearson's correlations between site-year means of meteorological variables (Section 2.2.4) and aboveground biomass or grain yield were evaluated for both fully-irrigated and rainfed conditions for the entire growth cycle and the pre- and post-sillking phases. Stepwise multiple-regression analysis (Kleinbaum *et al.*, 1998) was performed to explain the simulated variability in potential aboveground biomass and grain yield (dependent variables) on meteorological variables (independent variables). The objective was to determine whether using mean meteorological values for both the vegetative and reproductive phases as independent variables, instead of means for the entire crop growth cycle, can explain significantly more of the simulated variation in potential aboveground biomass and grain yield. Because there was a high degree of co-linearity between T_{mean} and T_{max}, and between T_{mean} and T_{min} (data not shown), stepwise regressions used either T_{mean} or both T_{max}, and T_{min}. Cumulative solar radiation was chosen as an independent variable instead of daily radiation because: (i) the former integrates both daily radiation and differences in hybrid maturity among locations (Table 2-2), and (ii) daily radiation and T_{max} were highly correlated ($r \approx 0.7$). Separate stepwise regression analyses ($p > 0.05$ for variable rejection) were performed with different sets of independent variables for (i) the entire crop cycle and (ii) both pre- and post-silking phases. Additional quadratic terms for temperature were added into the model to account for curvilinear responses. The predictive value of each variable was quantified in terms of its relative contribution to the regression sum of squares (%SSR), the latter computed as the difference between the total sum of squares and the residual sum of squares.

2.2.7. Boundary-function analysis

Quantile regression was used to derive maximum boundary functions for the relationships between simulated aboveground biomass or grain yield and seasonal water supply (ASW_S + growing-season rainfall + irrigation) or ET_C. Fully-irrigated (n = 295) and rainfed (n = 564) free-frost site-years pooled across ASW_S scenarios (Cade and Noon, 2003). To derive the boundary function, seasonal water supply and ET_C values for the 200-800 mm and 200-600 mm intervals were split into ten classes; these ranges represent the water supply and ET_C levels in which grain yield is responsive to changes in water status. The 95th percentile of class biomass or yield was regressed against the water-availability or ET_C mid-point of each class using the software Blossom Version W2008 (Fort Collins Science Center, 2008).

Boundary functions derived for the aboveground biomass or grain yield *vs.* ET_C plots were compared against observed data for aboveground biomass (n = 263) or grain yield (n = 556) versus ET_C, obtained from the literature for maize grown in low-rainfall environments (see Appendix A1). In these studies maize relied on stored ASW, seasonal rainfall, and in some cases, irrigation. Reported ET_C was generally calculated as growing-season rainfall and irrigation plus the change in ASW of the root zone between sowing and harvest.

2.3. RESULTS

2.3.1. Model validation

The Hybrid-Maize model simulated yields reasonably well in the Western Corn Belt as 95% and 70% of predicted grain yield were within ±15% of measured values for fully-irrigated and rainfed crops, respectively, across a broad range of growth conditions and yield potential (Fig. 2-3). Grain yield was overestimated at very low observed yields (< 2 Mg ha^{-1}) and for two cases in the moderate yield range between 6 to 9 Mg ha^{-1}. Examination of climate data during the growing season for these four site-years identified severe water deficits during the 3 weeks immediately before and shortly after silking (data not shown). Although maize yields are highly sensitive to water deficits during the period immediately before and after silking through effects on pollination and kernel setting (Hall *et al.*, 1982, Westgate and Boyer, 1986), Hybrid-Maize does not explicitly simulate the direct effects of water deficits on kernel number. It is therefore likely the discrepancies between observed and simulated values in these four site-years were due to lack of adequate sensitivity in the Hybrid-Maize model to severe moisture deficits during the silking window.

2.3.2. Geospatial gradients of climate and crop water demand

Geospatial trends in meteorological variables differed for cumulative solar radiation and T_{mean} depending on the crop growth time period and direction. For example, while T_{mean} was relatively constant across the longitudinal gradient of the Western Corn Belt, cumulative solar radiation increased from 2560 MJ m^{-2} in the east to 3203 MJ m^{-2} in the west, and this gradient was most pronounced in the pre-silking growth period (Fig. 2-4a-c). In contrast, cumulative solar radiation was relatively constant across the latitudinal gradient while T_{mean} for the entire growing season increased from 18.5 ºC in the north to 22.4ºC in the south, and this increase was most pronounced in the post-silking phase (Fig. 2-4d-f). T_{max} increased from north-south in both the pre- and post-silking phases ($p <$ 0.001, $r^2 = 0.61$ and 0.76, respectively), while no latitudinal variation in T_{min} was detected (data not shown). The length of the free-frost season also increased from north-south (data not shown). Although T_{mean} was similar across longitude, the mean thermal amplitude (*i.e.*, the difference between mean daily minimum and maximum temperature) increases dramatically in the east-west direction ($p < 0.001$, $r^2 = 0.92$).

Longitudinal gradients were found for seasonal rainfall and ET_O (Fig. 2-4g-i), whereas both variables were relatively constant across the north-south direction (data not shown). From east to west, rainfall decreases from 555 to 210 mm while ET_O increases from 485 to 790 mm. At all locations, the variability in rainfall during the entire growing season was much greater across years than ET_O (coefficient of variation [CV] = 0.40 for rainfall vs. 0.12 for ET_O), especially during the post-silking phase (Fig. 2-4g-i). Trends in the recommended rainfed plant population closely follow the east-west rainfall and ET_O gradients, reflecting management adaptation to reduced water supply (Fig. 2-2).

2.3.3. Seasonal patterns of rainfall, maximum ET_C and water-stress index

The mean and standard error (20-year) for rainfall during the entire growing-season were 286±33 and 398±26 mm at Akron CO and Mead NE, respectively. At both locations, maximum ET_C (820±13 at Akron and 607±14 mm at Mead, respectively) exceeds growing-season rainfall by a large margin. While rainfall exceeds ET_C in May, which is the first month after planting, it remains well below crop water demand throughout the remainder of the growing season, especially at Akron (Fig. 2-5a, b), which represents the western edge of the longitudinal gradient in this study (Fig. 2-1). Maximum crop water demand peaks in late June and early July, about two months after planting and remains relatively high throughout the remainder of the growing season (Fig. 2-5a, b). Annual variation in rainfall was large at both locations for each 20-day period throughout the growing season (CV = 0.85 and 0.75 at Akron and Mead, respectively) compared to the much smaller annual variation in ET_C (CV = 0.21 and 0.25, respectively). Simulated average WSI indicates that maize grown in the Western Corn Belt will experience transient water stress events from pre-silking phase about 60 days after sowing until physiological maturity in most years with the magnitude and probability of water stress increasing as the season progresses (Fig. 2-5c, d). Average stress severity was greater and more likely at Akron than in Mead, in agreement with the east-west gradient in rainfall and ET_O (Fig. 2-4g-i). At both locations, greater stored soil moisture at sowing reduced the magnitude of water stress from pre-silking to maturity although the magnitude of reduction was relatively small (Fig. 2-5c, d).

2.3.4. Geospatial patterns in potential and water-limited yields

Potential grain yield was not correlated with longitudinal or latitudinal trends ($p > 0.10$), although highest yields were mostly achieved at intermediate latitudes (40°N-42.5°N, data not shown). In contrast, there was a strong latitudinal gradient in potential aboveground biomass ($p < 0.01$, $r = -0.81$), mostly due to warmer daytime temperatures during the entire crop cycle. In rainfed crops, there was a sharp longitudinal gradient of aboveground biomass ($p < 0.001$, $r = 0.76$) and grain yield ($p < 0.001$, $r = 0.81$), associated with seasonal rainfall and ET_O gradients (Fig. 2-4g-i). Mean simulated potential grain yield ranged from 11.4 to 16.1 Mg ha^{-1} across locations (mean: 14.4 Mg ha^{-1}) with a relatively small degree of annual variation (CV = 0.11). Maximum simulated grain yields (≈ 17-20 Mg ha^{-1}) were similar to those reported by Duvick and Cassman (1999) for the same region. Rainfed yields were lower and considerably more variable: 'high' and 'low' ASW_S scenarios averaged 8.8 and 7.6 Mg ha^{-1}, respectively (associated CVs = 0.27 and 0.42). Mean potential aboveground biomass yield averaged 26.1 Mg ha^{-1} (range: 21.8-30.5 Mg ha^{-1}, CV = 0.07), while mean rainfed aboveground biomass yield was 16.9 and 15.5 Mg ha^{-1} for the 'high' and 'low' ASW_S scenarios, respectively (associated CVs = 0.20 and 0.27). For both irrigated and rainfed conditions, the CVs for total aboveground biomass yield were smaller than for grain yield, and this difference was greatest in rainfed situations.

Highest aboveground biomass yields were found at locations where the length of the growing season and the recommended hybrid maturity resulted in large cumulative solar radiation values (Table 2-3, Fig. 2-6a), and where crops were subjected to warm temperatures during the vegetative phase (Table 2-3, Fig. 2-6b). Geospatial variation on potential grain yield was most closely associated with post-silking cumulative solar radiation (Table 2-3, Fig. 2-6c). The significant parabolic relationship between simulated grain yield and post-silking T_{mean} suggests that both high (≈ > 25ºC) and low (≈ < 20ºC) mean daily temperatures during grain filling reduce grain yield potential (Fig. 2-6d). High post-silking T_{mean} reduced grain-filling duration ($p < 0.001$, $r^2 = 0.59$) and also increased maintenance respiration as simulated by Hybrid-Maize (data not shown). On the other hand, low post-silking T_{mean} reduced both photosynthetic rates and kernel-growth rates (data not shown), and, in most cases, these effects were not offset by the increase in the grain-filling duration associated with low post-silking temperatures.

Stepwise regressions were performed separately for all site-years ($n = 351$) and frost-free site-years ($n = 295$) to test for inconsistencies in the final regression model but the variables selected and their coefficients were of similar magnitude and sign (data not shown). Stepwise multiple-regression that included meteorological means for both vegetative and reproductive growth phases explained 86% and 70% of the variation on simulated potential aboveground biomass and grain yield, respectively (data not shown). Pre- and post-silking cumulative solar radiation and pre-silking maximum daily temperature had the greatest influence on potential aboveground biomass (%SSR = 35, 30, and 29%, respectively; $p < 0.001$). In contrast, potential grain yield was most closely related to post-silking cumulative radiation and mean daily temperature (%SSR = 89 and 6%, respectively; $p < 0.001$). The negative effects of high temperatures on potential grain yield during grain filling were reflected by a significant quadratic term for post-silking

T_{mean} ($p < 0.005$). These results were consistent with the single-factor relationships quantified by Pearson's correlation (Table 2-3) and regression (Fig. 2-6). Stepwise regressions using meteorological variable means for the entire growing season explained considerably less of the variation in simulated potential aboveground biomass and grain yield (adjusted $r^2 = 0.70$ and 0.48, respectively).

2.3.5. Boundary functions for the relationship between grain yield or aboveground biomass and water supply or ET_C

Fitted boundary functions for the relationship between aboveground biomass or grain yield and seasonal water supply had slopes of 46.0±2.3 and 27.7±1.8 kg ha^{-1} mm^{-1}, respectively (Fig. 2-7a, b). Slopes of the fitted linear regression using the same database were 33.0±0.2 and 19.3±0.4 kg ha^{-1} mm^{-1} for aboveground biomass or grain yield, respectively, and x-intercepts were similar to the ones shown for the boundary functions in Fig. 2-7a, b (data not shown). When seasonal water supply was large, the relationship between yield and water supply weakened due to water losses by percolation below root zone and residual soil water at physiological maturity. Simulated percolation averaged 105±6 mm for fully-irrigated crops and 96±5 and 20±4 mm for rainfed crops under 'high' and 'low' ASW_S, respectively, and was associated with pre-silking rainfall ($p < 0.001$, $r^2 = 0.74$, 0.78, and 0.56). Residual ASW at harvest averaged 120±2 mm for fully-irrigated crops and 88±3 and 52±4 mm for rainfed crops under 'high' and 'low' ASW_S, respectively, and was associated with post-silking rainfall ($p < 0.001$, $r^2 = 0.55$, 0.63, and 0.59).

The relationship between aboveground biomass or grain yield and seasonal ET_C (Fig. 2-7c, d) had much less scatter compared to plots against seasonal water supply (Fig. 2-7a, b). Fitted boundary functions had slopes (≈ TE_S) of 54.4±5.6 and 37.0±1.3 kg ha^{-1} mm^{-1}, respectively, and *x*-intercepts of 25 and 85 mm (≈ seasonal soil evaporation) (Fig. 2-7c, d) which corresponds closely with the range of seasonal soil evaporation simulated by Hybrid-Maize for the Western Corn Belt (range: 25-79 mm; 7-34% of the seasonal ET_C). Slopes of the fitted linear regression using the same database were 49.5±0.9 and 31.7±0.6 kg ha^{-1} mm^{-1} for aboveground biomass or grain yield, respectively, and the values of the x-intercepts were 75 and 145 mm (data not shown). Across the 18 locations in our study, the mean simulated ET_C for fully irrigated crops was 618±5 mm, which is close to the value of 610 mm reported for irrigated maize crops grown in the Western Corn Belt (Loomis and Connor, 1992). Although Hybrid-Maize does not account for other yield-reducing factors such as nutrient deficiencies, weeds, and pests, there was a wide range in yield of up to 6 Mg grain ha^{-1} for both rainfed and fully-irrigated crops at a given amount of ET_C (Fig. 2-7c, d). Hybrid-Maize simulations identified the primary causes for this variation, which include: (i) post-silking cumulative radiation and temperature under irrigated conditions, (ii) intensity of post-silking water stress under rainfed conditions, and (iii) site differences and within site annual variation in evaporative demand (determined largely by the solar radiation, vapour pressure deficit, and wind speed), and water loss from soil evaporation (data not shown).

Compared to reported values from the literature, the boundary function estimated in our current study appears to be broadly applicable to measured values of yield or aboveground biomass and ET_C from field studies conducted at a number of locations around the world (Fig. 2-8). Nearly all of the measured data points fell well below the attainable productivity delimited by the boundary functions for both aboveground biomass and grain yield. Despite identifying the reasons for differences across and within environments was not an objective of this research, we speculate that gaps between the boundary function and the observed data were associated with both environmental limitations such as evaporative demand and water supply distribution, as well as other non-water-related factors such as plant population, nutrient supply, and biotic stresses. Likewise, runoff and percolation below root zone, generally not measured for ET_C calculation, contribute to the observed gap between the boundary function and actual yields, especially in locations with high rainfall.

2.4. DISCUSSION

Maize yields were simulated over a period of 20 years at 18 locations across the Western Corn Belt using current best recommended management practices for each location. Geospatial gradients in radiation, temperature, rainfall, and ET_O gradients had a large impact on maize potential productivity under both irrigated and rainfed conditions. Potential grain yields were closely associated with cumulative incident solar radiation and temperature during the post-silking period while rainfed grain yields were largely governed by the available water supply from initial soil moisture and rainfall.

Maize maximum TE_S for grain yield was estimated to be about 37 kg ha^{-1} mm^{-1} and 54 kg ha^{-1} mm^{-1} for total aboveground biomass. These values are within the upper range of field-measured TE_S calculated as the ratio of grain yield or aboveground dry matter to total transpiration (Tanner and Sinclair, 1983, Otegui *et al.*, 1995, Kremer *et al.*, 2008, Suyker and Verma, 2009). TE_S for aboveground biomass corrected by mean daytime vapor pressure deficit during the crop growing season (average across locations: 1.57 ± 0.05 kPa) yielded 85.6 kg kPa ha^{-1} mm^{-1}, a value closed to the theoretical TE_S calculated for maize equals to 98.3 kg kPa ha^{-1} mm^{-1} (Tanner and Sinclair, 1983) and within the range of field-measured values (55-138 kPa ha^{-1} mm^{-1}, median 84.6 kg kPa ha^{-1} mm^{-1}; see previous references for TE_S values). The boundary TE_S for grain yield estimated here is well above reported values for winter cereals (20-22 kg grain ha^{-1} mm^{-1}; Passioura, 2006, Sadras and Angus, 2006), winter pulses (9-20 kg grain ha^{-1} mm^{-1}; Loss *et al.*, 1997, Zhang *et al.*, 2000; Siddique *et al.*, 2001), and oilseed crops (8-15 kg grain ha^{-1} mm^{-1}; Specht *et al.*, 1986, Hocking *et al.*, 1997, Robertson and Kirkegaard, 2005; Grassini *et al.*, 2009), which, like our maize estimates, are based on grain yields at standard commercial moisture content for each crop. Except for cases when severe water stress occurs during the sensitive anthesis-silking window (which determines maize kernel number), maize TE_S for grain yield is expected to be greater than that for other crops because maize carbon fixation occurs via the C4 pathway and the energetic cost of its grain is smaller compared to protein-rich legume seed or oilseed crops (Sinclair *et al.*, 1984, Loomis and Connor, 1992).

Analysis of yield determining factors by simulation modeling and regression analysis indicated that meteorological variables estimated separately for pre- and post-sliking periods had greater explanatory power than use of estimates for the entire growing season. Whereas the greatest potential aboveground biomass yield occurs at locations and in years with a long growing-season and a late maturing hybrid, which together maximize cumulative solar radiation, warmer temperatures during the vegetative growth phase also contribute to higher potential biomass yields—presumably due to increasing photosynthetic rates and/or a more rapid leaf area expansion which leads to an early canopy closure (Andrade *et al.*, 1993, 1996, Westgate *et al.*, 1997).

Based on recommended planting dates and hybrids, maize crops experience water stress during the reproductive growth period in a high proportion of years throughout the Western U.S. Corn Belt, although the severity of stress increases along the east-west rainfall gradient. While greater stored soil water content at sowing diminishes the intensity of the water stress during the growing season, it does not eliminate it. Given the high probability of water stress, recommended plant populations decreased with the east-west rainfall gradient to avoid depletion of soil moisture during the vegetative stage due to a larger leaf area than required to achieve maximum water-use efficiency for grain yield. Field studies in Western Nebraska confirm the benefits of reducing maize plant population as the available water supply decreases (Lyon *et al.*, 2003).

The maximum boundary functions estimated in our study and regional estimates of ET_C are useful tools for diagnosing productivity constraints to maize yields in water-limited and irrigated environments. Boundary functions values provide benchmarks that can be used by agronomists and researchers to set realistic productivity goals for a specific irrigated or rainfed environment. Where measured values fall well below these thresholds, the yield gap can be closed by identifying and correcting non-water-related factors that constrain productivity, such as nutrient deficiencies, diseases, and weeds. Differences in the coefficients of the boundary functions shown in Fig. 2-7 (a, b) versus the ones shown in Fig. 2-7(c, d) may indicate greater than average water loss from percolation, surface runoff, or a significant amount of unused water left in the soil profile at maturity. In fact, simulations showed that water losses from percolation and runoff often occur in the same year that a maize crop experiences yield-reducing water stress. Thus, management practices that reduce these losses through healthier root systems, appropriate tillage and residue management, and precise irrigation scheduling and amounts will increase the fraction of available water removed by the crop, decrease the risk or severity of water stress, and improve crop water productivity.

Overall, this study has defined the limits for maize productivity in the Western Corn Belt. Radiation and temperature determine the ceiling for potential productivity while water supply imposes an upper limit for rainfed crops. Highest potential grain yields are expected at locations where the length of the post-silking phase is maximized, keeping temperatures over the optimum range for kernel growth and carbon net assimilation. Boundary functions derived from this study provide a useful benchmark to analyze water-limited productivity. Finally, simulated and reported data indicate that maize seasonal TE is well above to that reported for winter cereals, grain legumes and oilseed crops.

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Table 2-1. Dataset for Hybrid-Maize validation for rainfed and fully-irrigated crops.

Location	Seasons	*n*	Yield (Mg ha^{-1})[a]	Sources
Fully-irrigated crops				
Bellwood, NE [†]	2003	1	20.2	Dobermann and Walters (2004)
Brunswick, NE	2003	1	20.7	Dobermann and Walters (2004)
Cairo, NE	2003	1	20.5	Dobermann and Walters (2004)
Clay Center, NE	2002, 2005, 2006	3	17.2-19.2	Yang *et al.* (unpublished data)
Edgar, NE	2007	1	16.1	Yang *et al.* (unpublished data)
Geneva, NE	2007	1	15.7	Yang *et al.* (unpublished data)
Hordville, NE	2007	1	15.1	Yang *et al.* (unpublished data)
Lincoln, NE	1999-2003	11	14.2-20.9	Yang *et al.* (2004), Dobermann and Walters (2004)
Mead, NE	2002-2007	2	15.4-18.6	Yang *et al.* (unpublished data)
North Platte, NE	2003-2006	3	15.7-16.8	Yang *et al.* (unpublished data)
Paxton, NE	2003	1	19.1	Dobermann and Walters (2004)
Scandia, KS	2003	2	16.2-18.7	Dobermann and Walters (2004)
York, NE	2007	1	17.6	Yang *et al.* (unpublished data)
West Point, NE	2007	1	17.8	Yang *et al.* (unpublished data)
Rainfed crops				
Champaign, IL	2003	1	19.4	Dobermann and Walters (2004)
Clay Center, NE	2005-2006	2	3.9-7.7	Yang *et al.* (unpublished data)
Manchester, IA	2002	1	16	Yang *et al.* (2004)
Mead, NE	2001, 2003, 2005	3	7.7-9.9	Walters *et al.* (unpublished data)
North Platte, NE	1992-1995, 2005, 2006	6	0.6-13	Payero *et al.*, 2006, Yang *et al.* (unpublished data)

[a] Measured yields at standard moisture, 0.155 kg H_2O kg^{-1} grain.
[†] Locations and corresponding USA state (IL: Illinois; IA: Iowa; KS: Kansas; Nebraska: NE).

Table 2-2. Dataset for modeling analysis of fully-irrigated and rainfed maize yield at different locations in Western U.S. Corn Belt using historical climate data (1986-2005).

Location	Dominant soil series	% of total agricultural land [a]	Planting date [b]	Hybrid-maturity [c]	Plant population [d]	Frost incidence [e]
Akron, CO [‡]	Platner	35	130	1400	32000	15
Alliance, NE	Creighton	57	128	1220	†	20
Ames, IA	Clarion	30	115	1472	78000	10
Brooking, SD	Kranzburg-Brookings	15	124	1172	74000	20
Central City, NE	Holder	20	119	1524	63000	25
Champion, NE	Goshen	10	125	1417	35000	25
Clay Center, NE	Hastings	43	113	1510	54000	20
Concord, NE	Moody	33	123	1382	67000	20
Elgin, NE	Moody	22	121	1438	54000	15
Garden City, KS	Richfield	40	121	1524	44000	0
Holdrege, NE	Holdrege	91	117	1510	49000	10
Lincoln, NE	Aksarben	37	113	1524	69000	10
Manhattan, KS	Reading	12	106	1510	59000	0
Mead, NE	Yutan	22	120	1524	64000	5
North Platte, NE	Holdrege	18	124	1405	44000	20
O'Neill, NE	Jansen	53	123	1340	54000	25
Ord, NE	Holdrege	20	125	1450	58000	20
West Point, NE	Moody	40	120	1510	64000	25

[a] Percentage of the dominant soil series land suitable for maize production with respect to the total agricultural land in the area (710 km^2) surrounding each location. Data derived from STATSGO (USDA, 1994) and SSURGO (USDA, 1995) databases.

[b] Day of year.

[c] Sowing-to-physiological maturity growing degree days (T_b= 10ºC).

[d] Plant population for rainfed crops (plants ha^{-1}). Plant population for fully-irrigated crops was set at 80000 plants ha^{-1} at all locations.

[e] Percentage of years with early frost during grain-filling.

[‡] Location and corresponding USA state (CO: Colorado; IL: Illinois; IA: Iowa; KS: Kansas; Nebraska: NE; SD: South Dakota).

[†] No significant rainfed maize production at this location.

Table 2-3. Pearson's correlations coefficients between the simulated aboveground biomass or grain yield of fully-irrigated (n = 295) or rainfed (n = 564) maize and means of environmental factors computed for the entire crop cycle (ECC), or the pre- (Pre-S) or post-silking (Post-S) phases. Site-years in which a frost occurred during grain-filling were not included.

	Fully-irrigated crops		Rainfed crops [a]	
Environmental factor	Aboveground biomass	Grain Yield	Aboveground biomass	Grain Yield
Daily radiation				
Pre-S	0.53***	-0.03	-0.38***	-0.35***
Post-S	0.56***	-0.25***	-0.40***	-0.43***
ECC	0.58***	-0.15**	-0.42***	-0.42***
Cumulative radiation				
Pre-S	0.51***	0.22***	-0.18**	-0.16**
Post-S	0.74***	0.75***	0.06	0.15*
W	0.72***	0.55***	-0.08	0.02
Mean temperature				
Pre-S	0.23***	-0.02	-0.21***	-0.22***
Post-S	0.07	-0.40***	-0.27***	-0.37***
ECC	0.21***	-0.32***	-0.27***	-0.34***
Maximum temperature				
Pre-S	0.49***	-0.11	-0.42***	-0.41***
Post-S	0.19**	-0.56***	-0.45***	-0.53***
ECC	0.39***	-0.35***	-0.48***	-0.52***
Minimum temperature				
Pre-S	-0.01	0.11	-0.20***	0.17**
Post-S	-0.13*	-0.38***	-0.03	-0.14*
ECC	-0.07	-0.16**	0.08	-0.01
Rainfall				
Pre-S	-0.26**	0.13***	0.60***	0.52***
Post-S	-0.29	0.25***	0.59***	0.53***
ECC	-0.09	0.30***	0.71***	0.67***
Relative humidity				
Pre-S	-0.26***	0.13*	0.39***	0.38***
Post-S	-0.29***	0.25***	0.58***	0.57***
ECC	-0.31***	0.21***	0.54***	0.53***
Reference ET				
Pre-S	0.53***	-0.03	-0.53***	-0.45***
Post-S	0.56***	-0.25***	-0.50***	-0.63***
ECC	0.58***	-0.15**	-0.63***	-0.57***

Asterisks indicate correlation at *p<0.05, **p<0.01, and ***p<0.001.
[a] Data pooled across initial ASW scenarios.

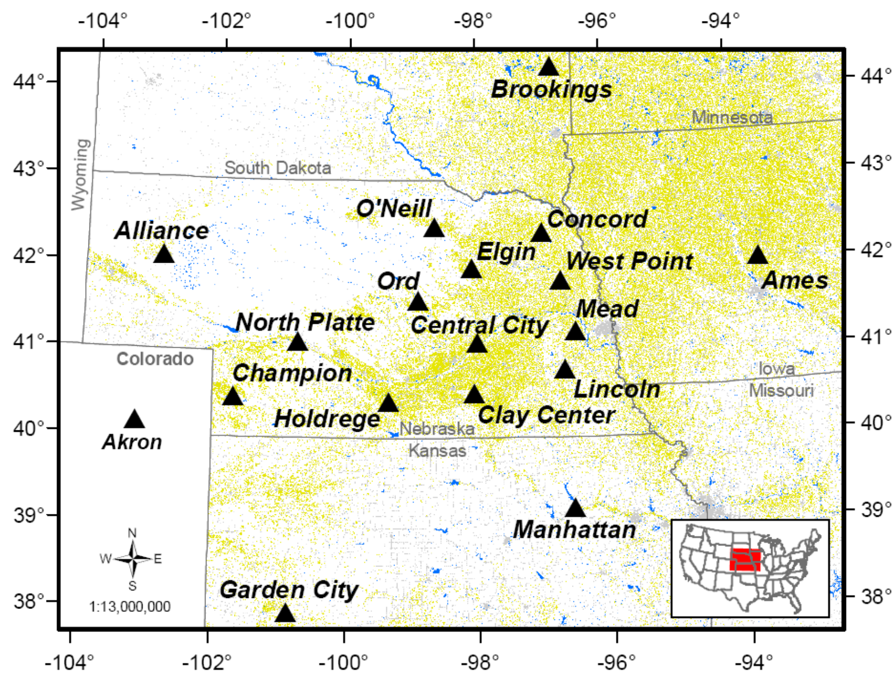

Figure 2-1. Map of the Western U.S. Corn Belt. States are named and their boundaries shown. Triangles indicate sites of meteorological stations used in this study. Inset shows location of area within U.S. Maize (yellow), water (blue), and urban (grey) areas are shown, except for Wyoming and Colorado (data not available).

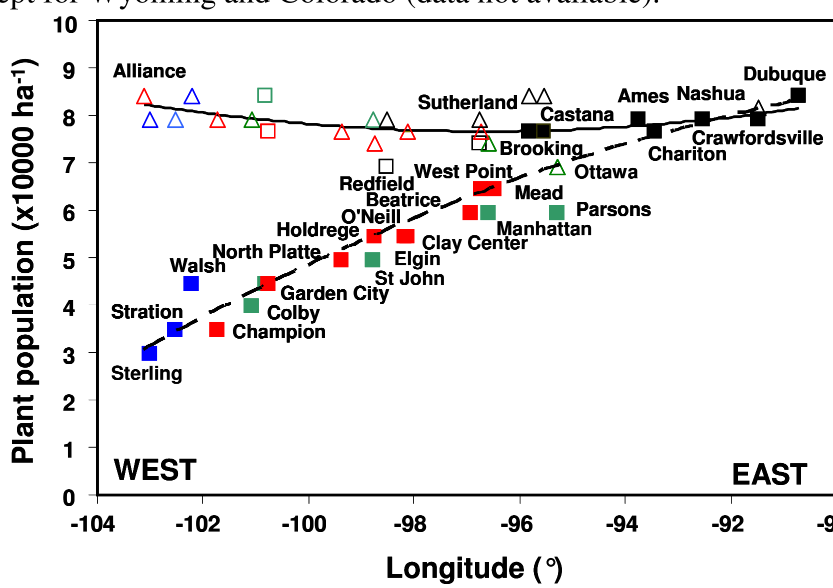

Figure 2-2. Actual recommended plant populations for irrigated (open triangles, solid line) and rainfed crops (solid squares, dashed line) plotted against longitude in Western U.S. Corn Belt. Locations are named and colours indicate the state to which each location belongs (Colorado: blue; Iowa: black; Kansas: green; Nebraska: red; South Dakota: black). At some eastern locations, symbols for irrigated and rainfed crops are overlapped. Second-order polynomial functions were fitted for rainfed (y = -0.016x^2 - 2.65x - 101.5; p<0.001; r^2 = 0.88) and fully-irrigated crops (y = 0.013x^2 + 2.60x + 133.3; p>0.10; r^2 = 0.21). Both functions are shown for comparison, regardless their significance.

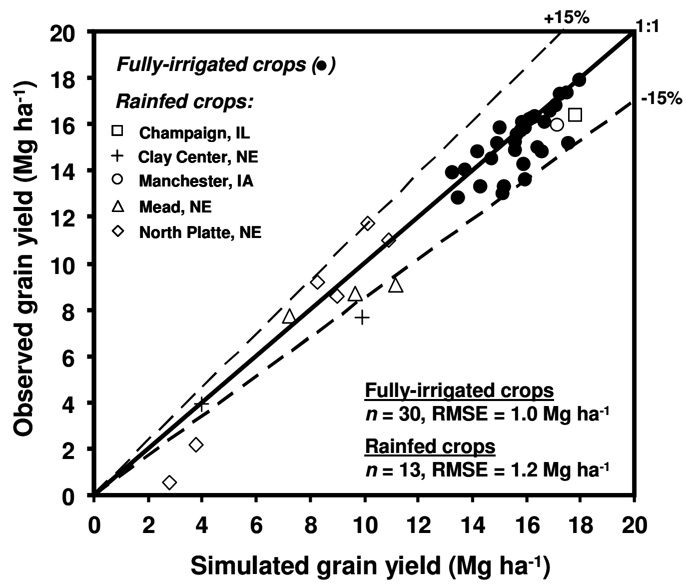

Figure 2-3. Observed vs. simulated yields for a test set of fully-irrigated and rainfed maize crops grown in the U.S. Corn Belt (see Table 2-1 for more details). Diagonal solid line: 1:1 ratio; dotted lines: ±15% deviation from 1:1 line. Separate root mean square errors (RMSE) for fully-irrigated and rainfed crops are shown.

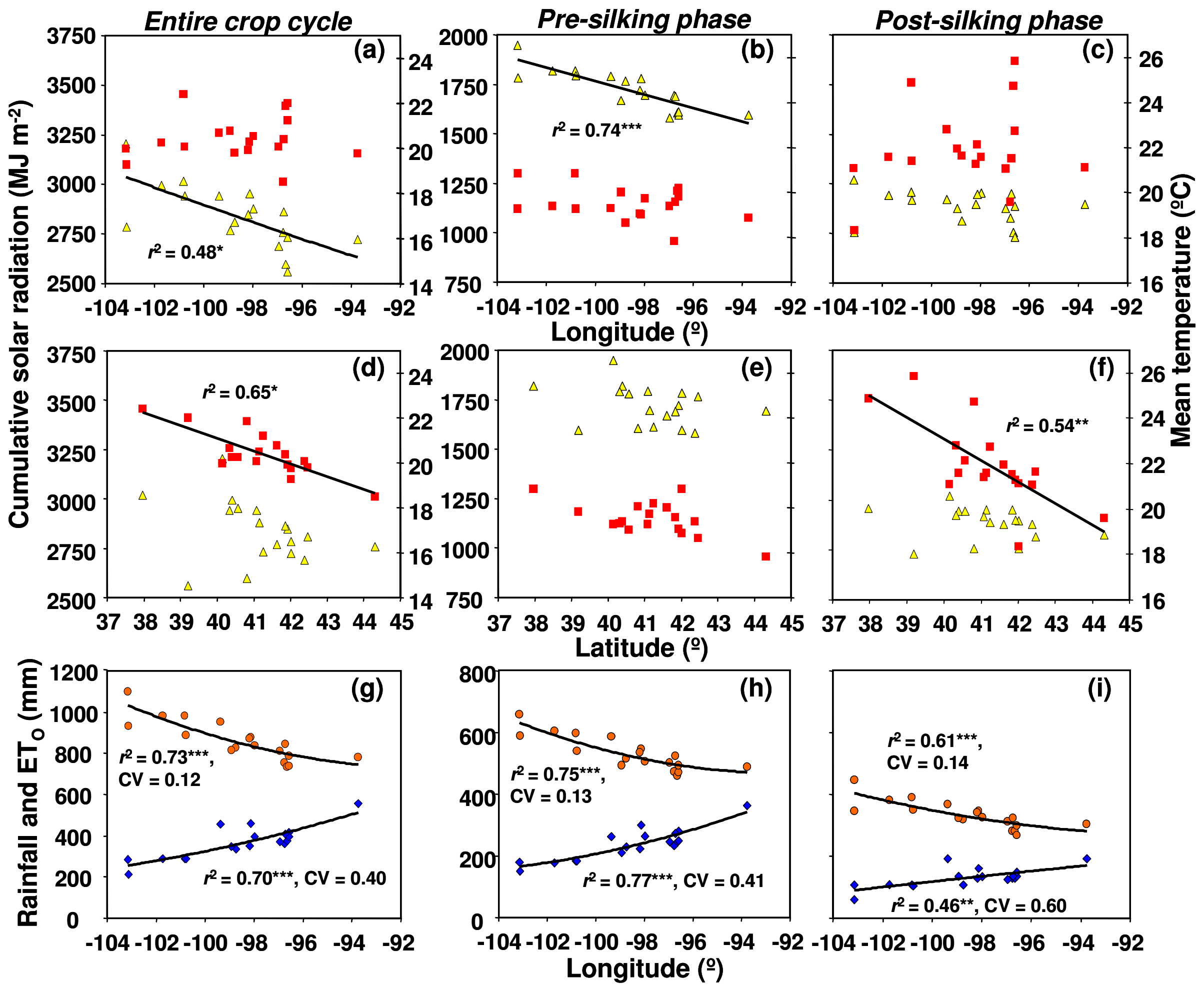

Figure 2-4. Longitudinal and latitudinal gradients of selected meteorological factors during the entire crop cycle (left panels), the pre-silking phase (central panels), and the post-silking phase (right panels). (a, b, c, d, e, f) Cumulative solar radiation (yellow triangles) and mean temperature (red squares); (g, h, i) Cumulative rainfall (blue diamonds) and reference evapotranspiration (ET_O, orange circles). No latitudinal gradients of cumulative rainfall and ET_O were found, thus, these plots are not shown. Each point is the 20-y average for a given location. Crops affected by early frost were not accounted. SE ranges, across locations, between 34-82, 15-52, and 21-38 MJ m^{-2} for cumulative solar radiation and between 0.2-0.3, 0.2-0.4, and 0.3-0.6ºC for mean temperature, for the entire crop cycle, pre-, and post-silking phases, respectively. Average inter-annual coefficients of variation (CV) for cumulative rainfall and ET_O are shown. Asterisks indicate correlation at *$p < 0.01$, **$p < 0.001$, and ***$p < 0.0001$.

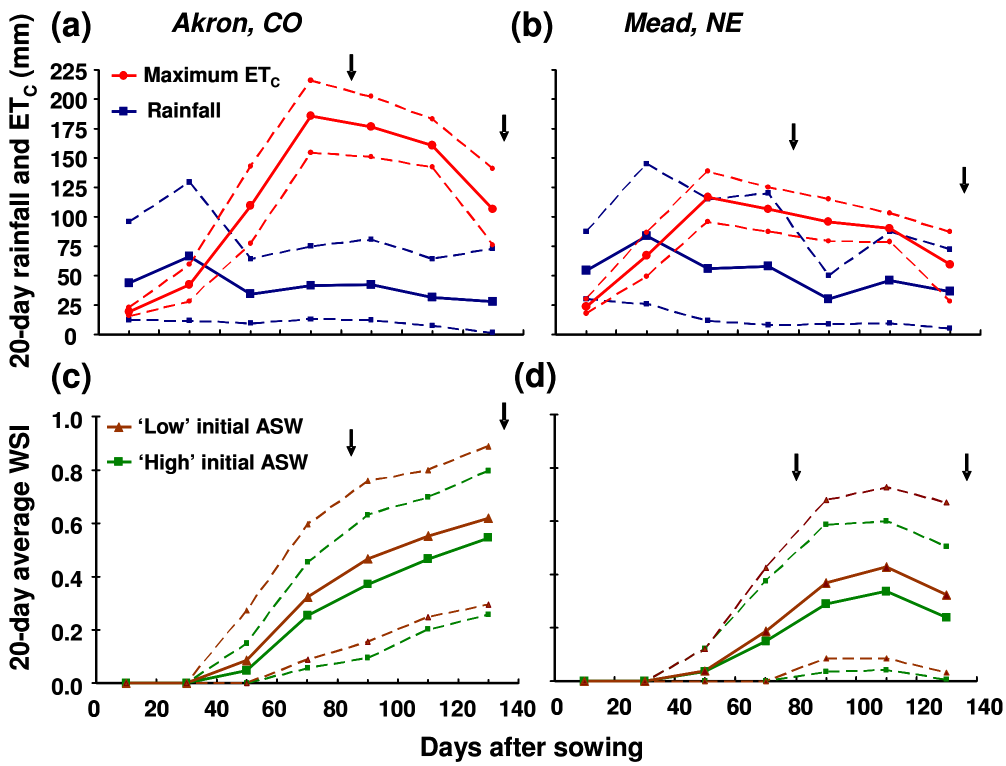

Figure 2-5. Patterns of long-term (a, b) 20-day cumulative rainfall and crop evapotranspiration, under non-limiting water supply (ET_C), and (c, d) 20-day average water-stress index (WSI) in simulated rainfed crops for two scenarios of available soil water (ASW) at sowing. Each point represents a 20-day interval. Solid thick lines: means; dashed thin lines: upper and lower terciles. Data come from selected stations in the area of interest, Akron, CO (left panels) and Mead, NE (right panels) (see Fig. 2-1). Sowing dates were 10-May and 30-April at Akron and Mead, respectively. Vertical arrows indicate average simulated dates of silking and physiological maturity (left and right arrows, in each figure, respectively).

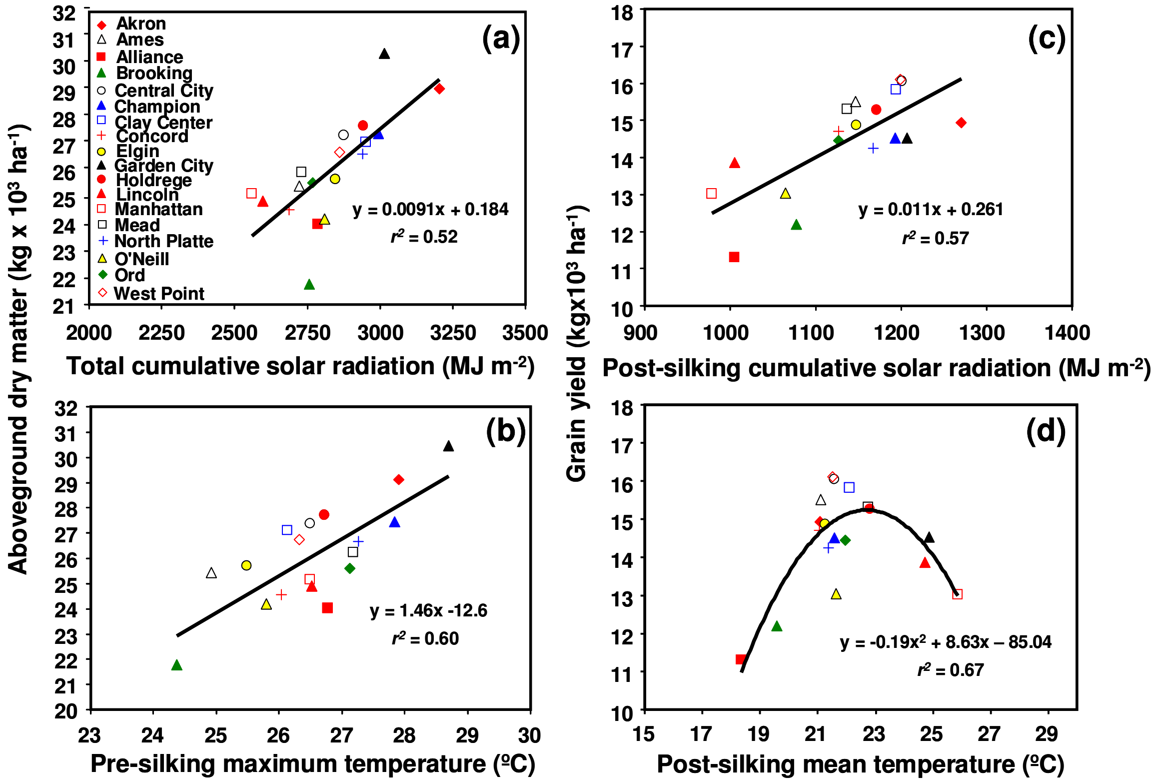

Figure 2-6. Simulated potential aboveground dry matter yield as a function of total cumulative solar radiation and mean daily pre-silking maximum temperature (a, b), and simulated potential grain yield as a function of cumulative solar radiation and average mean temperature during the post-silking phase (c, d). Each point is the 20-y average at each simulated location (excluding those site-years in which a frost occurred during grain filling) in the Western U.S. Corn Belt (see Fig. 2-1). All relationships were highly significant ($p < 0.001$).

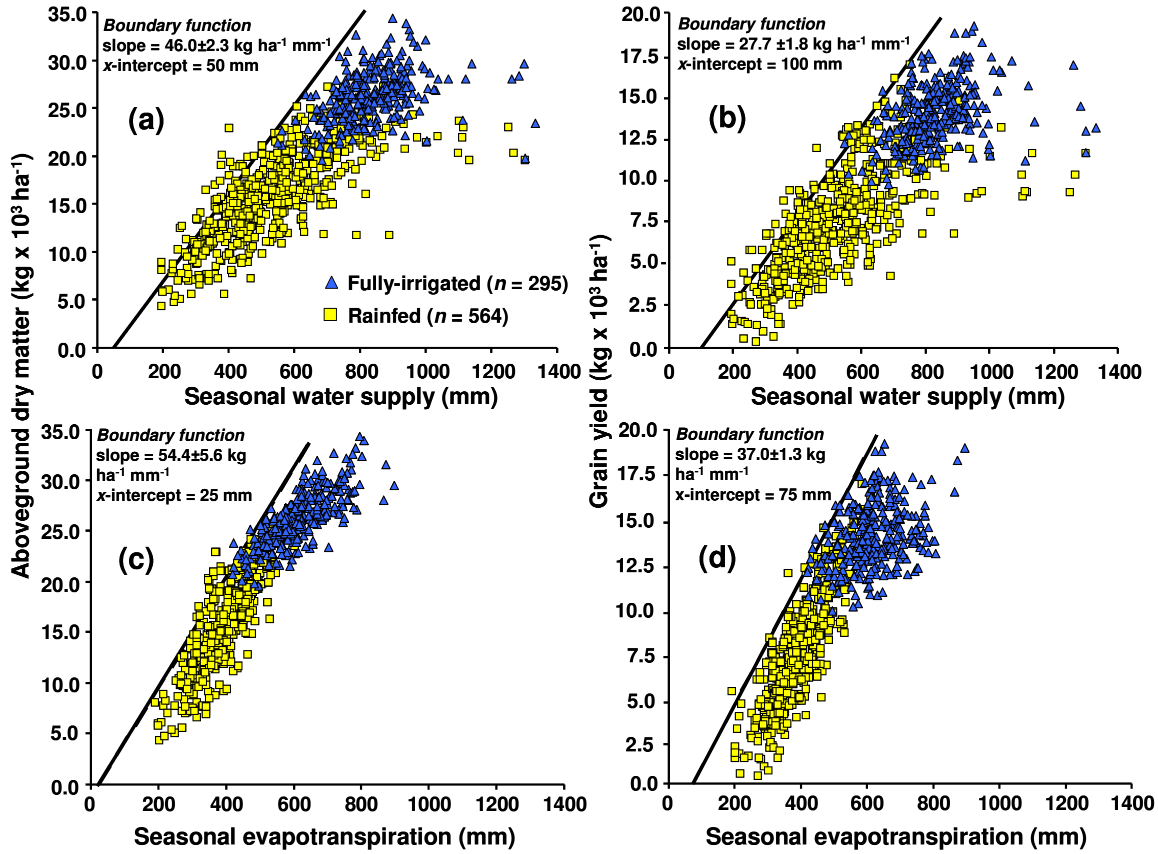

Figure 2-7. Relationships between simulated aboveground dry matter (left panels) and grain yield (right panels) and seasonal water supply (a, b), and simulated crop evapotranspiration (c, d). Rainfed crops category includes the two initial ASW_S scenarios. Lines are the boundary functions for water productivity (a, b), and water-use efficiency (c, d). Slopes (±SE) and *x*-intercepts of the boundary functions are shown. Site-years in which a frost occurred during grain filling were not included.

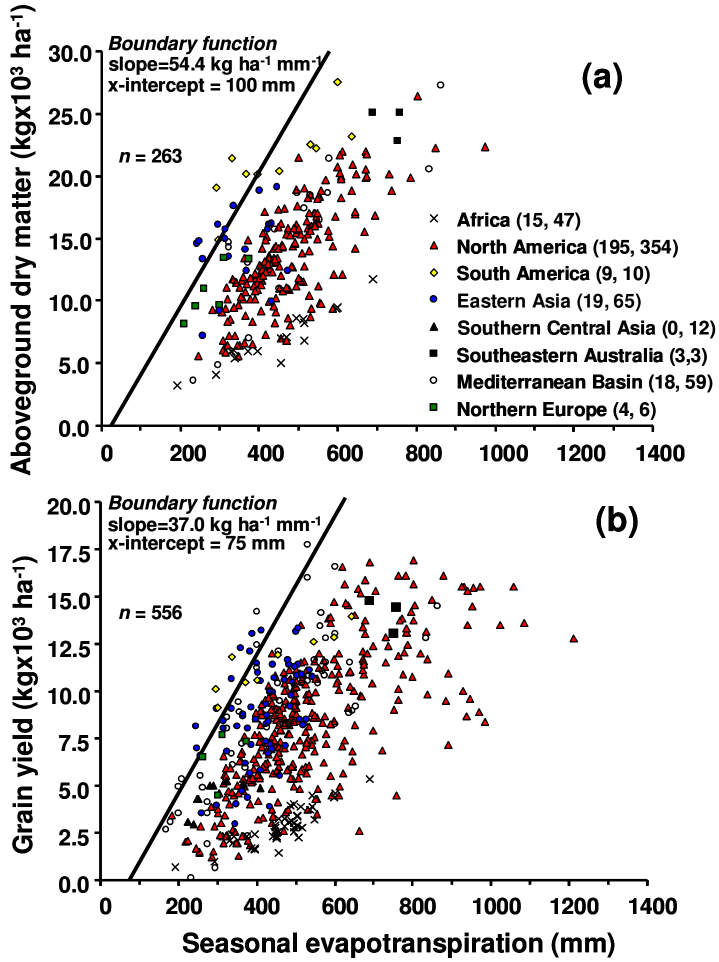

Figure 2-8. Reported observed maize (a) aboveground dry matter and (b) grain yield / crop evapotranspiration relationships in experiments conducted in low rainfall environments (see Appendix A1 for data sources). For each region, the number of cases for aboveground dry matter and grain yield is indicated, in this order, between parentheses. The solid lines are the boundary functions for water-use efficiency shown in Fig. 2-7c, d; their slopes and *x*-intercepts are shown.

CHAPTER 3: SOIL WATER RECHARGE IN A SEMI-ARID TEMPERATE CLIMATE OF THE CENTRAL U.S. GREAT PLAINS [2]

ABSTRACT

The amount of soil water at the beginning of the growing season has a large impact on crop yields in rainfed agriculture, especially in semi-arid regions and in years with below-average rainfall in more humid climates. Robust algorithms are needed to estimate soil water storage before planting to aid crop management decisions. The main objectives of this paper are to investigate soil water recharge during the non-growing season (Oct 20 to May 1) in a semi-arid, temperate ecosystem in south-central Nebraska (USA) and to evaluate empirical models to estimate soil water content at the beginning of the summer-crop growing season. A database of soil water content measurements collected over five years at nine locations in south-central Nebraska was used to estimate available water-holding limits in the soil profile and to determine the change in available soil water during the non-growing season. Regression analysis was performed to analyze the relationship among soil water recharge, residual soil water (*i.e.*, soil water content at the end of the previous growing season), total precipitation, and available water-holding capacity (AWHC) in the root zone to 1.5 m. Precipitation storage efficiency (PSE) was calculated as the quotient of soil water recharge and total non-growing season precipitation. Predictive models to estimate soil water content at the beginning of

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summer-crop growing season were derived from these analyses. A large portion of the variation in soil water recharge was explained by residual soil water and precipitation. PSE averaged 28% across site-years; low PSE values were associated with high residual soil water and/or low AWHC. Two predictive models (linear and linear-plateau) that used residual soil water, total precipitation, and AWHC as independent variables explained 75-80% of the variation in the measured soil water content at the beginning of the summer-crop growing season. These empirical models represent a new tool to estimate soil water content by planting date of summer crops. Site-management conditions such as residue amount and its architecture, tillage system, soil texture, and terrain slope are not currently accounted for in these models and would likely improve predictive capacity.

Keywords: non-growing season, precipitation, soil water recharge, precipitation storage efficiency

Abbreviations: AW: total available water (mm); AWHC: available water-holding capacity (mm); AW%: total available water as percentage of AWHC; PSE: precipitation storage efficiency (%); TW: total soil water (mm); θ_v: volumetric soil water content; $\theta_{v\text{-}WP}$ and $\theta_{v\text{-}FC}$: soil water content at wilting point and field capacity, respectively.

3.1. INTRODUCTION

The water stored in a soil profile at the beginning of the growing season represents a significant fraction of total water supply available for crop transpiration (Loomis and

Connor, 1992). Variation in the initial soil water has an impact on subsequent yields of rainfed crop production (Lyon *et al.*, 1995; Nielsen *et al.*, 2002, 2008; Felter *et al.*, 2006). In irrigated crop production, knowledge of initial soil water status can help with irrigation scheduling, especially during the crop establishment and early vegetative growth stages. A fully recharged profile, for example, can delay and/or eliminate crop water deficit stress depending on rainfall amounts and distribution. Yields will increase and be more stable in a rainfed cropping-system where stress is ameliorated or avoided due to adequate initial soil water levels.

The amount of rainfall during the non-growing season does not by itself provide an estimate of the soil water recharge because there are unavoidable losses of water from soil evaporation, deep drainage, and runoff (O'Connell *et al.*, 2003; Dolling *et al.*, 2006; Monzon *et al.*, 2006). Also, the available water-holding capacity of each soil type imposes an upper limit to soil recharge beyond which further precipitation at the surface is destined to runoff and deep drainage (Loomis and Connor, 1992). Precipitation storage efficiency (≈ fallow efficiency, defined as the net change in soil water with respect to the total precipitation; Mathews and Army, 1960) is determined by soil type, precipitation amount and distribution, evaporative demand, and the water left in the soil by the previous crop (Loomis and Connor, 1992). Precipitation storage efficiency can also be modified by agricultural practices such as tillage system, weed control, and residue management (Smika, 1990; Pannkuk *et al.*, 1997; Nielsen *et al.*, 2005). Reported precipitation storage efficiencies range from -50 to 40% across published studies. Most of this work has focused on rainfed wheat-fallow systems in the U.S. Great Plains (Smika, 1970; Fenster and Wick, 1982; Farahani *et al.*, 1998; Nielsen *et al.*, 2010) and southeastern Australia (*e.g.*, Schultz, 1971; French, 1978). Initial soil water status in maize systems where soil water recharge occurs during winter has received much less attention despite the importance of initial soil water to maize yields, especially in the Western U.S. Corn Belt (Neild *et al.* 1987; Grassini *et al.* 2009). Similarly, Nielsen *et al.* (2008) demonstrated responses of dryland maize yields to initial soil water in northeastern Colorado that were highly variable depending on mid-season rainfall amounts.

Beyond the importance of initial soil water to crop productivity there are other issues associated with agronomic decisions. Estimation of soil water content at the beginning of the growing season based on empirical algorithms would be useful for crop consultants and farmers to support management decisions such as selection of the most appropriate crop species, plant population density, hybrid-maturity, nutrient application, and irrigation schedule (*e.g.*, Neild *et al.*, 1987; Lyon *et al.*, 2003; Moeller *et al.*, 2009). Moreover, these initial estimates could be made a few months in advance using three inputs: weather information to date, expected values (forecast and outlook), and selected historical weather data. Because initial soil water is required input for most crop simulation models (Sinclair *et al.*, 2007), a robust algorithm to estimate initial soil water could help improve accuracy of crop simulations, which can be used to estimate crop production risk and economic profits at a regional scale (*e.g.*, Ferreyra *et al.*, 2001).

The objectives of this work are to: (i) evaluate relationships among soil water content, residual soil water, and total precipitation during the non-growing season in south-central Nebraska (USA), (ii) identify the most sensitive factors affecting precipitation storage efficiency, and (iii) develop empirical algorithms that estimate available soil water at the beginning of the summer-crop growing season with reasonable accuracy.

3.2. MATERIALS AND METHODS

3.2.1 Site

The study region (*ca.* 2,268,000 ha) is located in south-central Nebraska, USA (40ºN-41.1ºN; 98.3ºW-100.8ºW). The area has flat to rolling terrain and supports both irrigated and rainfed field cropping systems. Soils are deep without physical impediments to root growth. Dominant soils are mapped in the Holdrege, Coly, and Uly series, all with silt loam texture. Maize and soybean are the dominant crops. Crop water requirements exceed growing-season rainfall; the balance must be met from irrigation and stored soil water that accumulates during the non-growing season period. The amount of soil water present at time of planting in spring depends on the water remaining in the profile after the prior season's crop and water entering the soil from rainfall and snowmelt. It tends to be relatively dry in autumn and soil freezes in winter; therefore, most profile replenishment occurs in spring. In addition to sublimation of snow during the winter and evaporation from soil surface early (autumn) and late (spring) during the non-growing period, rapid snowmelt coupled with spring rains can result in runoff and deep percolation in some years.

3.2.2 Soil water data

Daily soil water measurements were taken during 5 years (2004-2008) at 9 sites under native ungrazed short-grass prairie vegetation in south-central Nebraska (Table 3-1). Measurement sites were restricted to flat or gently sloping terrain. Soil water data were obtained using Theta probes with readings taken at four depths: 10, 25, 50, and 100 cm. Details on water measurements and equipment calibration can be found in Hubbard *et al.* (2009) and Sridhar and Hubbard (2010). Following Craine *et al.* (2002) grass species are either tall grass characterized by high density, fine roots that extend deep into the soil or short grass characterized by fine roots that do not extend deep into the soil. The root zone here was taken to be 150 cm consistent with a short grass prairie. Soil water content readings were converted to volumetric soil water content (θ_v) using calibration curves specific to the Theta probe in three soil types: sandy, silty, and clay (Hubbard *et al.*, 2009). We assumed that the measurement levels (10, 25, 50, and 100 cm) represent the approximate midpoint in each of four depth intervals (0-12.5, 12.5-37.5, 37.5-75, and 75-150 cm). Whilst soil water content measured at 100 cm represents a proxy for average soil water content in the 75-150 cm layer, we expect the error due to this approximation to be small. The reason is because fluctuations at 100-cm depth during the non-growing season were much smaller than at 10, 25, and 50 cm depths (13 *versus* 35, 45, and 50%, respectively). Total soil water (TW) in the rooting zone was calculated as the sum of the products between θ_v and layer thickness for the four layers. Only data collected prior to Nov 1 and after Mar 1 were used to determine the beginning and ending soil water during non-growing season to avoid any uncertainty in soil water measurements when the soil profile is frozen.

Soil water content at wilting point ($\theta_{v\text{-}WP}$) and field capacity ($\theta_{v\text{-}FC}$) for each layer and each site was derived from soil water patterns from five years of data as proposed by Ritchie (1981) and Ratliff *et al.* (1983). $\theta_{v\text{-}WP}$ was assumed to be equal to the minimum θ_v measured during the spring-summer growing season. In three of nine sites, measured θ_v in the bottom layer (75-150 cm) did not appear to reach the water content near the wilting point. For these sites, $\theta_{v\text{-}WP}$ was assumed to be equal to the value estimated for the 37.5-75 cm layer. $\theta_{v\text{-}FC}$ was estimated from the soil water dynamic over periods of time (typically 2 to 10 d) after a large rainfall event that resulted in soil water content above field capacity for these silt loam soils. After such a rainfall event, soil water content based on Theta probe measurements decrease rapidly until drainage ceased. At that point, the slope of the soil water content curve over time decreased, indicating that further losses were not due to drainage but were instead due to evapotranspiration. The point at which there was an abrupt change in slope of the soil water content curve was taken as $\theta_{v\text{-}FC}$. For each layer, available soil water was calculated as the difference between actual θ_v and $\theta_{v\text{-}WP}$ while available water-holding capacity was calculated as the difference between $\theta_{v\text{-}FC}$ and $\theta_{v\text{-}WP}$. The sum of the products between available soil water or available water-holding capacity and layer thickness was calculated to estimate the total available water (AW) or available water-holding capacity (AWHC) in the rooting zone, respectively, both expressed in mm. Throughout this chapter, AW is also expressed as percentage of the AWHC (AW%).

3.2.3 Data analysis

A weather station was maintained at each site (details can be seen in Hubbard *et al.*, 1983) that recorded daily values of incident solar radiation, maximum and minimum temperature, relative humidity, wind speed and direction, and precipitation. Wintertime precipitation observations were obtained from the surrounding NOAA Cooperative (COOP) Observer Weather Data Network and used with inverse distance weighting function to estimate non-growing season precipitation, which includes rainfall, snowfall, and sleet expressed as water equivalent (see NOAA-NWS, 2007 and available URL for details on precipitation measurements). Total non-growing season precipitation was calculated from Oct 20 to May 1. These dates correspond to the average first killing frost (assumed to occur when minimum temperature ≤ -4.4 ºC) and maize planting date in the region, respectively. Precipitation pattern was characterized by summing precipitation data over 15-day intervals. Sites were classified according to the AWHC into 'low' (259-276 mm) and 'high' AWHC (308-319 mm). Soil water content on Oct 20 was taken as the residual total or available soil water content while soil water content on May 1 of the following year was taken as the total or available soil water at the beginning of the summer-crop growing season. Soil water recharge, defined as the net soil water change during the non-growing season, was calculated as the difference in the soil water content on May 1 and Oct 20 of the previous year. Positive or negative values indicate net soil water recharge or loss, respectively, during the non-growing season. One site-year (Holdrege, 2007-2008 non-growing season) was excluded from the analysis because estimated soil water recharge exceeded total non-growing season precipitation by 50 mm. Finally, precipitation storage efficiency (PSE) was calculated as the ratio of soil water recharge to non-growing season precipitation and expressed as a percentage.

Linear, linear-plateau, and second order polynomial functions were used to validate relationships between soil water content on May 1 (dependent variable) and total non-growing season precipitation and residual soil water (independent variables). Multiple-regression analysis was performed (i) to test the effects of residual soil water, total precipitation, AWHC and their interactions (independent variables) on soil water recharge and soil water content on May 1 (dependent variables), and (ii) to determine the best predictive model for estimation of soil water content on May 1. Before proceeding with the analysis, the degree of co-linearity among independent variables and the effect of quadratic terms were tested. Reference evapotranspiration was not included in the analysis due to a high co-linearity with precipitation ($p < 0.0001$). Simple correlation was used to investigate relationships between PSE, total precipitation, residual soil water and AWHC.

3.3. RESULTS

3.3.1. Soil water-holding capacity and non-growing season precipitation pattern

Available water-holding capacity in the rooting zone was large for all sites, ranging from 259 and 319 mm, which is representative of arable soils in this region (Table 3-1). While $\theta_{v\text{-}FC}$ was similar across depth intervals and sites, $\theta_{v\text{-}WP}$ varied by more than two-fold. Average total non-growing season precipitation was slightly above the 20-y mean (long-term average) value (168 versus 142 mm, respectively) and varied greatly across the site-years in this study (64 to 354 mm) (Table 3-2). Year-to-year variation in total precipitation was much greater than geospatial variation (average coefficients of variation [CV]: 60 versus 20%, respectively) (Table 3-2). During the four non-growing seasons, precipitation was concentrated in the last 45 days (March-April) of the non-growing period, which, on average, accounted for 70% of the total precipitation (Fig. 3-1). The concentration of precipitation during this period was greater than the long-term average (43-53% across locations).

The inverse distance weighting method for daily precipitation during winter months proved satisfactory for estimating non-growing season precipitation. For example, at Mead, NE the non-growing season precipitation estimates, from 1990-1991 to 2006-2007, compared favorably to independent measurements of precipitation in the vicinity with an r^2 of 96% and a standard error of observed to estimated values of only 15 mm, which is 7% of total precipitation during this period.

3.3.2. Residual soil water and non-growing season precipitation

Large variation in $AW\%_{20\text{-Oct}}$ and $AW\%_{1\text{-May}}$ was observed across sites and years (Table 3-2). $TW_{1\text{-May}}$ was positively related to $TW_{20\text{-Oct}}$ ($p < 0.001$, $r^2 = 0.63$) and total non-growing season precipitation ($p < 0.01$, $r^2 = 0.20$). Similar relationships were found between $AW_{1\text{-May}}$ and $AW_{20\text{-Oct}}$ ($p < 0.001$, $r^2 = 0.29$), and between $AW_{1\text{-May}}$ and total precipitation ($p < 0.005$, $r^2 = 0.32$). The sum of both independent variables (*i.e.*, residual soil water [1.5 m] plus precipitation) explained 88 and 77% of total variation in $TW_{1\text{-May}}$ and $AW\%_{1\text{-May}}$, respectively (Fig. 3-2a, c). Maximum $TW_{1\text{-May}}$ and $AW\%_{1\text{-May}}$ was reached at about 700 and 450 mm total from residual soil water plus precipitation, respectively. A similar relationship was found for $AW_{1\text{-May}}$ and $AW_{20\text{-Oct}}$ plus total precipitation although maximum $AW_{1\text{-May}}$ values differed depending on the AWHC (Fig. 3-2b). Differences between Fig. 3-2a and Fig. 3-2b reflect variation in the estimated $\theta_{v\text{-WP}}$ across sites (Table 3-1). When the independent variable was normalized by the AWHC at each site, separate lineal-plateau functions were fitted according to soils with AWHC of 259 to 276 mm versus 308 to 319 mm (Fig. 3-2d). The major difference between the two fitted regressions was the $AW\%_{1\text{-May}}$ observed at high values of the independent variable (81 and 91% for 'low' and 'high' AWHC). Nevertheless, a common linear-plateau function for both categories of AWHC accounted for 75% of the variation in $AW\%_{1\text{-May}}$ (SE = 12.2%):

$$AW\%_{1\text{-May}} = -19.3 + 84.7 \times [(AW_{20\text{-Oct}} + \text{precipitation}) / \text{AWHC}]$$
$$\text{if } [(AW_{20\text{-Oct}} + \text{precipitation}) / \text{AWHC}] < 1.24 \qquad \text{[Eq. 3-1a]}$$

$$AW\%_{1\text{-May}} = 86$$
$$\text{if } [(AW_{20\text{-Oct}} + \text{precipitation}) / \text{AWHC}] \geq 1.24 \qquad \text{[Eq. 3-1b]}$$

To summarize, the four plots shown in Fig. 3-2 indicate that (i) soil water content at the beginning of the summer-crop growing season is highly variable and much of that variation can be explained by the residual soil water and total precipitation, (ii) the positive *x*-intercept observed in all the plots of $TW_{1\text{-May}}$ and $AW_{1\text{-May}}$ versus residual soil water plus total precipitation indicates unavoidable water losses during the non-growing season, and (iii) maximum $AW_{1\text{-May}}$ approaches but never equals AWHC.

Multiple-regression analysis confirmed previous results as 43% of the variation in $AW\%_{1\text{-May}}$ was explained by differences in $AW\%_{20\text{-Oct}}$, 44% by total non-growing season precipitation, and 10% by their interaction (Table 3-3a). No difference in the analysis was observed when $AW_{20\text{-Oct}}$ was used as independent variable instead of $AW\%_{20\text{-Oct}}$. After discarding the non-significant terms ($p > 0.05$) a linear model that includes $AW\%_{1\text{-May}}$ as dependent variable and $AW\%_{20\text{-Oct}}$, total precipitation, and their interaction as independent variables was fitted using 2004-2005 data ($n = 18$). When validated against $AW\%_{1\text{-May}}$ data from the 2006-2007 period ($n = 17$), root mean square error between observed and predicted values was 10%, which represents 17% of the mean observed $AW\%_{1\text{-May}}$, with an r^2 of 89% (data not shown). Coefficients of the final algorithm were fitted using all site-years, and they had similar sign and magnitude as the coefficients derived from 2004-2005 calibration data:

$$AW\%_{1\text{-May}} = -15.5 + 1.09 \times AW\%_{20\text{-Oct}} + 0.29 * \text{precipitation} - 0.003 * AW\%_{20\text{-Oct}} * \text{precipitation} \quad \text{[Eq. 3-2]}$$

$$\text{Adjusted } r^2 = 0.80, \text{ SE} = 10.5\%, n = 35$$

Both linear-plateau (Eq. 3-1a, b) and linear (Eq. 3-2) regressions can be used to predict $AW_{1\text{-May}}$ after scaling $AW\%_{20\text{-May}}$ by AWHC. Root mean square error between observed and predicted $AW_{1\text{-May}}$ was 36 and 29 mm using Eq. 1 and 2, respectively, which represented 21 and 17% of the mean $AW_{1\text{-May}}$ value of 173 mm.

3.3.3. Soil water recharge and precipitation storage efficiency

Observed soil water change during the non-growing season indicates recharge at some locations (*e.g.*, Cozad and Minden) while no recharge or at times discharge was observed at other locations (*e.g.*, Grand Island and McCook) (Table 3-2). Averaged across locations, PSE was 28% with large variation across sites and years (associated CVs= 63 and 35%). Interestingly, PSE was tightly correlated to soil water recharge (Pearson's $r = 0.78$; $p < 0.001$) and weakly correlated to total precipitation ($r = 0.28$; $p = 0.08$). Although few observations approached the maximum PSE (*i.e.*, 100%) most of the data were below the maximums (Fig. 3-3a). For instance, 70% of the PSE values were between the 50% and -25% precipitation efficiency lines.

Multiple-regression analysis showed that while 59% of the variability in soil water recharge was explained by total precipitation, the remaining variation was explained by $AW\%_{20\text{-Oct}}$ (22%), $AW\%_{20\text{-Oct}}$ by precipitation interaction (11%), and AWHC (6%) (Table 3-3b). Although the effect of total precipitation on soil water recharge was expected, these results also indicated that PSE depended on the residual soil water and AWHC. For instance, when data in Fig. 3-3a were classified in three categories according to the percentage of residual available soil water (low [0-33%; $n = 17$], intermediate [33-66%; $n = 10$], and high $AW\%_{\text{Oct-20}}$ [66-100%; $n = 8$]), separate linear regressions were fitted ($r^2 = 0.70$, 0.68, and 0.56, respectively; associated p-values: <0.001, 0.003, and 0.03) with similar x-intercept (≈ 60 mm) but different slopes (0.72, 0.55, and 0.27, respectively) (data not shown). Similar results were found when the data were classified according to AWHC ('low' and 'high'): slopes of fitted linear regressions were 0.35 and 0.59, respectively ($r^2 = 0.35$ and 0.64; associated p-values: 0.04 and <0.001). A negative linear relationship between PSE and $AW\%_{20\text{-Oct}}$ explained 45% of the variation on soil water recharge across site-years (Fig. 3-3b). Even though the interaction between residual soil water and AWHC was not significant, negative PSE (*i.e.*, net discharge) were likely to occur at site-years with low AWHC and high residual soil water. Finally, no relationship between soil water recharge or PSE and precipitation distribution, frequency or intensity were found probably because non-growing season precipitation patterns were similar across years (Fig. 3-1).

3.4. DISCUSSION

The ultimate goal of the research was to develop a method to estimate initial soil water content at the beginning of the summer-crop growing season using easily accessible data. An issue is whether empirical relationships derived from data collected in level fields under a prairie plant community can serve as a proxy for developing such a method. Another concern is that these relationships do not account for site-year variations in precipitation distribution, evaporative demand, or slope. Soil water recharge may also vary according to the amount and architecture of residue left by previous summer crop species due to differences in capacity for trapping snow, impact on soil evaporation, and runoff prevention (Nielsen *et al.*, 2005, Merril *et al.*, 2007).

Despite these limitations, the algorithms derived can be taken as a first approximation to estimate soil water at the beginning of the growing season for summer crops in the U.S. Great Plains. A key assumption is that cropped fields behave as fields under prairie during the non-growing season. In our study, the dormant period was assumed to start on the average date of the first killing-frost. Plant residues in these prairie plots covered the ground throughout the winter when soil freezes. This situation is similar to fields under no-till and ridge-till management where crop residues are left on the surface, and thus the algorithms generated from prairie should approximate this condition. However, given the characteristics of the sites where the soil water data were obtained (silty loam soils on flat land), the algorithms developed here may be less suitable for use on annual summer crop fields with sandy or heavy soil texture and sloping terrain.

Input data for these algorithms are precipitation during the non-growing season, residual soil water at planting, and AWHC. Precipitation data can be obtained from a precipitation gauge at the site or from nearby weather stations. Residual available soil water from a previous maize crop can be assumed to be 50-60% and 30-40% of AWHC for irrigated and rainfed crops, respectively, based on unpublished simulated data obtained from a regional analysis on maize productivity which includes 20-y weather data at 18 locations across the Western Corn Belt (Grassini *et al.*, 2009). Finally, values of AWHC for dominant soil series can be retrieved from available soil databases (*e.g.*, SSURGO; USDA, 1995).

The algorithms were derived from a database that included a wide range of residual soil water content from the previous growing season and total non-growing season precipitation. Large variation in available soil water on May 1 observed across 35 site-years under prairie in south-central Nebraska was largely explained by precipitation and residual soil water from the preceding growing season. Thus, the assumption of fully-recharged profiles by the beginning of the summer-crop growing season at the western edge of the Corn Belt is not consistent with results from this study. On the other hand, the wide range of precipitation storage efficiency (*i.e.*, the amount of recharge per unit of precipitation) found in this study indicates interactions among residual soil water, precipitation, and AWHC. In agreement with the work of Fernandez *et al.* (2008) in semiarid central Argentina, low precipitation efficiencies were found at sites with high residual soil water and/or low AWHC. High precipitation efficiencies were observed in site-years with low residual soil water and consistent with values reported on no-till wheat stubble over similar months in northeast Colorado (USA) by Farahani *et al.* (1998) and Nielsen *et al.* (2010) (PSE = 66 and 81%, respectively).

The fact that PSE rarely exceeded 50% indicates substantial water losses during the non-growing season. These water losses (estimated as total non-growing season precipitation minus soil water recharge) averaged 113±11 mm across site-years (data not shown). Soil evaporation may represent an important component of these water losses. In another study, Suyker and Verma (2009) found total non-growing season evaporation to vary from 100 to 172 mm in eastern Nebraska depending on the amount of mulch biomass left by the previous crop. While early-spring transpiration may be considered negligible due to low evaporative demand and low leaf area index, the occurrence of drainage below root zone and runoff events of unknown magnitude is expected when the water input from snowmelt and spring rains exceeds soil AWHC and infiltration rates. More research is needed to quantify the relative contribution of these processes and others (such as snow movement from the field due to wind and sublimation) to the total water losses budget.

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Table 3-1. Geographical coordinates (decimal degrees), soil series, and estimated volumetric soil water content at field capacity ($\theta_{v\text{-}FC}$) and wilting point ($\theta_{v\text{-}WP}$) for four soil depths (0-12.5, 12.5-37.5, 37.5-75, and 75-150 cm) derived from measured soil water dynamics at nine locations in south-central Nebraska (2004-2008). The sum of soil water content between FC and WP represents available water-holding capacity of the root zone (AWHC, 0-150 cm) is also shown.

Location	Lat (°)	Long (°)	Soil series[†]	0-12.5 cm		12.5-37.5 cm		37.5-75 cm		75-150 cm		AWHC (mm)
				$\theta_{v\text{-}FC}$	$\theta_{v\text{-}WP}$	$\theta_{v\text{-}FC}$	$\theta_{v\text{-}WP}$	$\theta_{v\text{-}FC}$	$\theta_{v\text{-}WP}$	$\theta_{v\text{-}FC}$	$\theta_{v\text{-}WP}$	
Cozad	40.97	-99.95	Coly/Uly/ Holdrege silt loam	0.35	0.09	0.33	0.11	0.33	0.09	0.35	0.17	313
Curtis	40.63	-100.50	Coly/Uly silt loam	0.36	0.16	0.36	0.10	0.39	0.18	0.29	0.10	311
Grand Island	40.88	-98.50	Coly silt loam	0.36	0.19	0.38	0.23	0.38	0.20	0.40	0.20	276
Holdrege	40.33	-99.37	Holdrege silt loam	0.37	0.11	0.36	0.13	0.38	0.15	0.43	0.24	319
Holdrege 4N	40.50	-99.35	Holdrege silt loam	0.35	0.13	0.38	0.24	0.39	0.16	0.38	0.16	314
Kearney	40.72	-99.02	Coly silt loam	0.35	0.11	0.37	0.19	0.37	0.15	0.41	0.21	308
McCook	40.23	-100.58	Holdrege/ Coly/Keith silt loam	0.39	0.10	0.39	0.19	0.39	0.23	0.38	0.23	259
Minden	40.52	-99.05	Holdrege silt loam	0.37	0.12	0.36	0.11	0.33	0.12	0.28	0.10	308
Smithfield	40.58	-99.67	Holdrege silt loam	0.37	0.12	0.38	0.17	0.39	0.22	0.33	0.16	275

[†] Coly, Uly, Keith, and Holdrege soil series are classified as Typic Ustorthent, Typic Haplustoll, Aridic Argiustoll, and Typic Argiustoll, respectively (USDA-NRCS).

Table 3-2. Mean (±SE) percentage of available soil water on Oct 20 and May 1 (AW%20-Oct and AW%1-May, respectively), total non-growing season precipitation, soil water recharge, and precipitation storage efficiency (PSE). Data collected in nine sites in south-central Nebraska over four non-growing seasons. Ranges are indicated between parentheses.

Site	$AW\%_{20\text{-Oct}}$ (%)	$AW\%_{1\text{-May}}$ (%)	Precipitation (mm)	Recharge (mm)	PSE (%)
Cozad	16±5	45±6	166±39	90±17	58±9
	(7-29)	(29-55)	(93-272)	(60-140)	(47-85)
Curtis	26±6	52±12	144±44	82±45	47±25
	(11-37)	(19-76)	(72-264)	(-14-201)	(-20-95)
Grand Island	68±9	71±5	171±38	9±16	-1±15
	(41-79)	(59-80)	(71-257)	(-31-49)	(-43-29)
Holdrege	42±8	77±12 †	197±55	89±40 †	51±11 †
	(22-60)	(54-95)	(76-334)	(0-190)	(29-67)
Holdrege 4N	27±13	46±18	176±62	61±37	24±12
	(3-56)	(17-93)	(65-354)	(-7-163)	(-10-46)
Kearney	51±14	61±17	169±47	29±22	11±10
	(26-84)	(23-94)	(71-297)	(-9-84)	(-6-28)
McCook	72 ± 4	68 ± 5	156 ± 58	-10±14	-17±16
	(62-82)	(56-82)	(64-314)	(-47-22)	(-64-7)
Minden	26±9	52±12	163±51	81±45	49±16
	(8-41)	(25-81)	(71-305)	(7-211)	(4-76)
Smithfield	33 ± 11	59 ± 13	170 ± 53	72 ± 31	39±6
	(18-64)	(31-85)	(71-311)	(26-130)	(23-52)

† 2007-2008 non-growing season was not included because estimated soil water recharge exceeded total non-growing season precipitation by 50 mm.

Table 3-3. Multiple-regression analysis for (a) percentage of available soil water on May 1 and (b) soil water recharge. Co-linearity among variables was not significant (Pearson's $r < 0.10$, $p > 0.35$). Quadratic terms were not significant ($p > 0.10$). Independent variables were: percentage of available soil water on Oct 20 ($AW\%_{20\text{-}Oct}$), total non-growing season precipitation (P, mm), and available water-holding capacity (AWHC, mm).

(a)

Source of variation	d.f.	SS type I	% of SS [a]	F-test
$AW\%_{Oct\text{-}20}$	1	6,338	42.6	58.2 ***
P	1	6,616	44.4	61.0 ***
AWHC	1	271	1.8	2.5
$AW\%_{Oct\text{-}20}$ x P	1	1,419	9.5	13.0 **
P x AWHC	1	1	<0.1	0.1
$AW\%_{Oct\text{-}20}$ x AWCH	1	244	1.6	2.2
$AW\%_{Oct\text{-}20}$ x P x AWHC	1	2	<0.1	0.1
Error	27	2,939		
Total	34	17,830		

(b)

Source of variation	d.f.	SS type I	% of SS	F-test
$AW\%_{Oct\text{-}20}$	1	27,394	22.2	27.2 ***
P	1	72,861	59.0	72.2 ***
AWHC	1	7,434	6.0	7.4 *
$AW\%_{Oct\text{-}20}$ x P	1	13,555	11.0	13.4 ***
P x AWHC	1	856	0.7	0.9
$AW\%_{Oct\text{-}20}$ x AWCH	1	1,251	1.0	1.2
$AW\%_{Oct\text{-}20}$ x P x AWHC	1	171	0.1	0.2
Error	27	27,243		
Total	34	150,766		

Asterisks indicate significance at *$p < 0.05$, **$p < 0.01$, ***$p < 0.001$

[a] Percentage of the total sum of squares excluding the error.

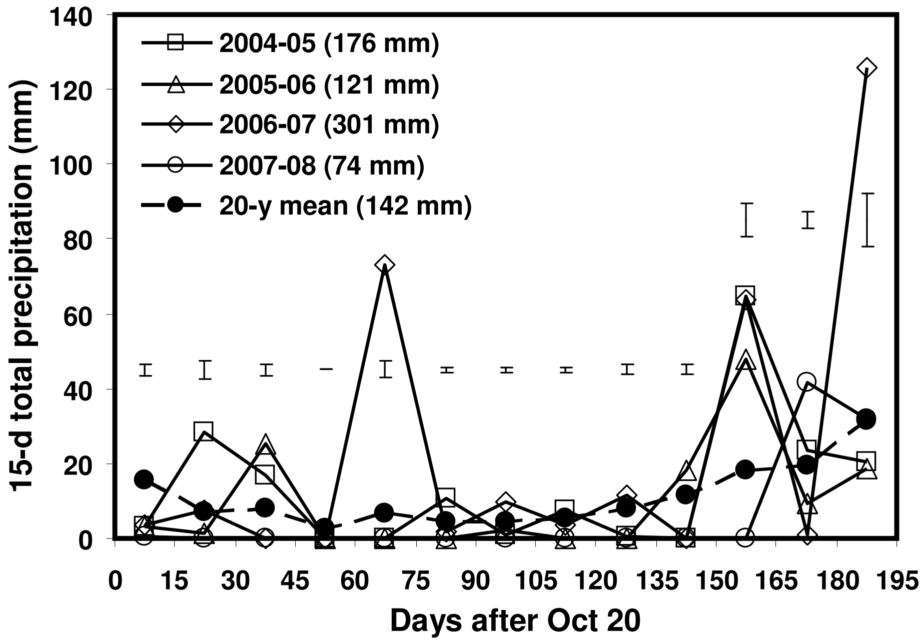

Figure 3-1. Patterns of 15-day total precipitation during the non-growing season (Oct 20 to May 1) for the 2004-2008 seasons (solid lines). The 20-y mean pattern is also shown (dashed line). Each point is the average for nine locations in south-central Nebraska (see Table 3-1). Vertical lines indicate ±SE of the mean. Mean total precipitation is indicated between brackets.

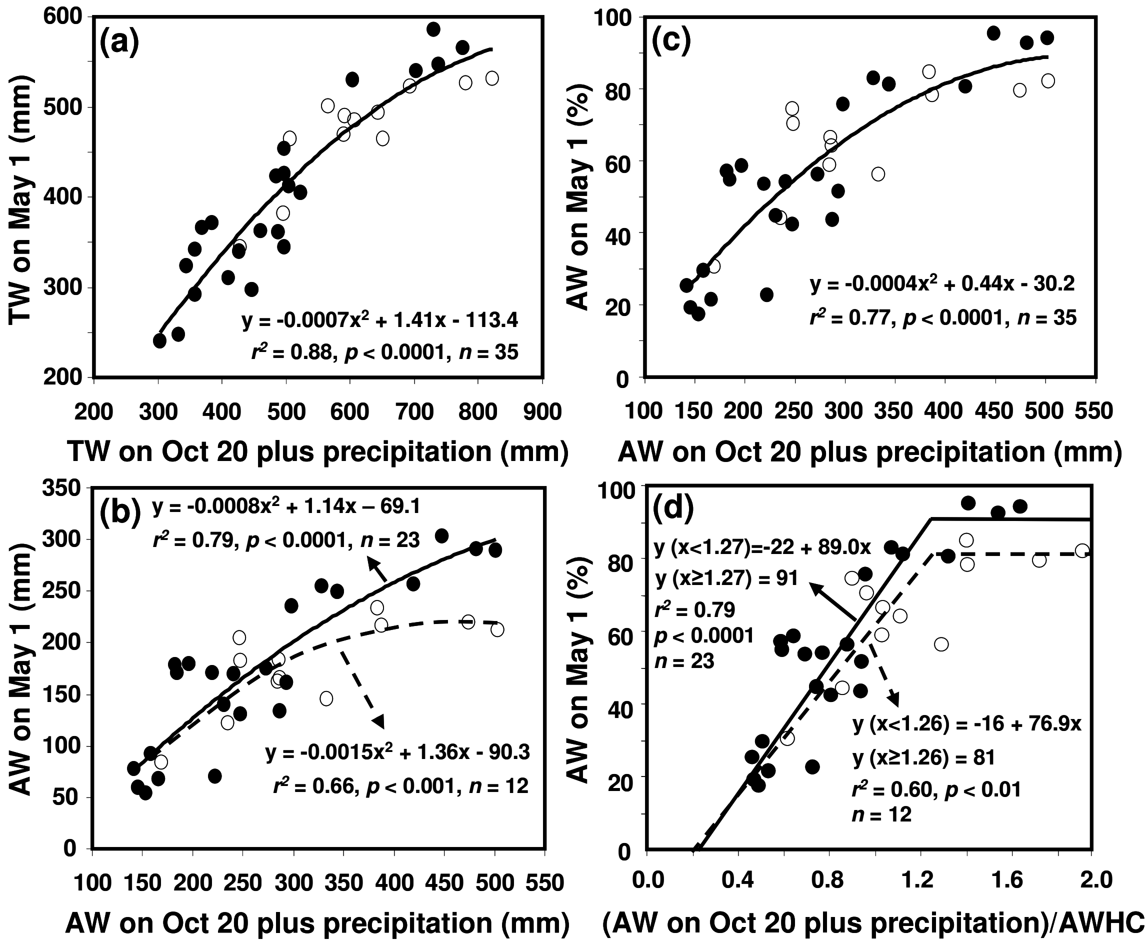

Figure 3-2. (a) Total soil water (TW) on May 1 as a function of TW on the preceding Oct 20 plus precipitation. (b) Available soil water (AW) on May 1 as a function of AW on Oct 20 plus precipitation. (c) Percent of AW on May 1 as a function of $AW_{20\text{-Oct}}$ plus precipitation and (d) as a function of $AW_{20\text{-Oct}}$ plus precipitation normalized by available water-holding capacity (AWHC). Total non-growing season precipitation was calculated from Oct 20 to May 1. Sites are classified according to 'low' (259-276 mm, ○ *open symbols*) and 'high' AWHC (308-319 mm, ● *closed symbols*).

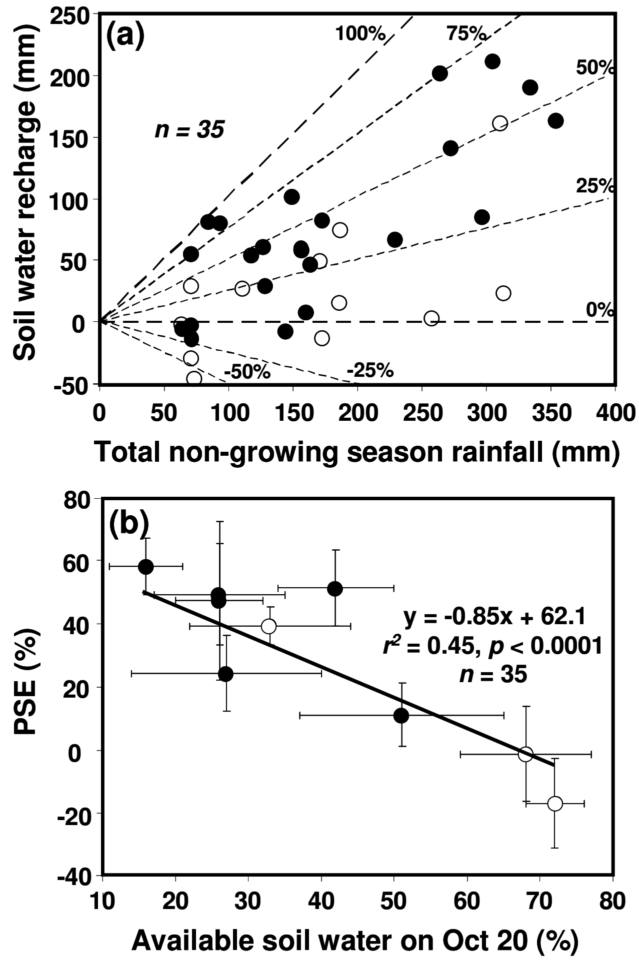

Figure 3-3. (a) Soil water recharge (calculated as the difference in soil water content between May 1 and previous Oct 20) as a function of total non-growing season precipitation. Dashed lines indicate constant precipitation recharge efficiency. (b) Precipitation storage efficiency (PSE) as a function of percentage of available soil water on Oct 20. Vertical and horizontal lines indicate ±SE of the mean for precipitation efficiency and $AW\%_{20\text{-oct}}$, respectively, for each site. Sites are classified according to 'low' (259-276 mm, O *open symbols*) and 'high' available water-holding capacity (308-319 mm, ● *closed symbols*).

CHAPTER 4: HIGH-YIELD IRRIGATED MAIZE IN WESTERN U.S. CORN BELT I. ON-FARM YIELD, YIELD POTENTIAL, AND IMPACT OF AGRONOMIC PRACTICES [3]

ABSTRACT

Quantifying the exploitable gap between average farmer yields and yield potential (Y_P) is essential to prioritize research and formulate policies for food security at national and international levels. While irrigated maize accounts for 58% of total annual maize production in the Western U.S. Corn Belt, current yield gap in these systems has not been quantified. A 3-y database (2005-2007) was used to quantify Y_P, yield gaps, and the impact of agronomic practices on both parameters in central Nebraska. The database includes field-specific values for yield, applied irrigation, and N fertilizer rate (n = 777). Y_P was estimated using a maize simulation model in combination with actual and interpolated weather records and detailed data on crop management collected from a subset of fields (n = 123). Yield gaps were estimated as the difference between actual yields and simulated Y_P for each field-year observation. Long-term simulation analysis was performed to evaluate the sensitivity of Y_P to changes in selected management practices. Results showed that current irrigated maize systems are operating near the Y_P ceiling. Average actual yield ranged from 12.5 to 13.6 Mg ha^{-1} across years. Mean N fertilizer efficiency (kg grain per kg applied N) was 10% greater than average efficiency in the USA. Rotation, tillage system, sowing date, and plant population density were the

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most sensitive factors affecting actual yields. Average yield gap was 11% of simulated Y_P (14.9 Mg ha^{-1}). Time trends in average farm yields from 1970-2008 show that yields have not increased during the past 8 years. Average yield during this period represented ~80% of Y_P ceiling estimated for this region based on current crop management practices. Simulation analysis showed that Y_P can be increased by higher plant population densities and by hybrids with longer maturity. Adoption of these practices, however, may be constrained by other factors such as difficulty in planting and harvest operations due to wet weather and snow, additional seed and grain drying costs, and greater risk of frost and lodging. Two key points can be made: (i) irrigated maize producers in this region are operating close to the Y_P ceiling and achieve high levels of N use efficiency and (ii) small increases in yield (<13%) can be achieved through fine tuning current management practices that require increased production costs and higher risk.

Keywords: Zea Mays L., maize, yield potential, on-farm yield, exploitable yield gap, simulation model.

Abbreviations: DOY: day of year; NRD: Natural Resources District; NUE: nitrogen use efficiency (kg grain kg^{-1} N); RM: hybrid-specific relative maturity (d); N: nitrogen; Y_P: yield potential (Mg ha^{-1}).

4.1. INTRODUCTION

Yield potential (Y_P) is defined as the yield of a crop cultivar when grown in an environment to which it is adapted, with nutrient and water non-limiting and pests and diseases effectively controlled (Loomis and Connor, 1992; Evans, 1993). Thus, Y_P is determined by genotype, plant population density and uniformity, and location-specific solar radiation and temperature regimes. The difference between on-farm yield and Y_P represents the exploitable yield gap (Cassman *et al.*, 2003; Lobell *et al.*, 2009). As farmers' yields approach Y_P (*i.e.*, diminishing exploitable yield gap), it becomes more difficult for farmers to sustain yield increases because further gains require the elimination of small imperfections in management of the crop system which is usually not economically viable. Hence, yield stagnation typically occurs when average farm yields reach about 80% of Y_P as was first observed in irrigated rice systems in Asia (Cassman, 1999). Accurate estimation of current exploitable gaps in major cropping systems of the world is therefore essential to estimate future food production capacity and help formulate policies and research to ensure local and global food security.

Although maize production must increase substantially to meet the rapidly increasing demand for food, livestock feed, and biofuel at a global scale (Cassman *et al.*, 2003; Cassman and Liska, 2007), little increase in maize Y_P has been observed during the last 30 years (Duvick and Cassman, 1999; Tollenaar and Lee, 2002). The Western U.S. Corn Belt (37ºN-45ºN; 92ºW-105ºW) includes one of the largest irrigated areas cultivated with maize in the world (3.2 million ha) mostly located in Kansas, Nebraska, and South Dakota (USDA-NASS, 2003-2008). Irrigated maize represents 43% of the total maize area (70% of the total irrigated cropland in Western Corn Belt) and accounts for 58% of the total annual maize production of 60 million Mg in this region. Duvick and Cassman

(1999) reported Nebraska state-level yield to be approximately 50% below the Y_P estimated from reported contest-winning yield levels (18.2 Mg ha^{-1}). Farmers who win these contests, however, use practices that are not likely to be economically viable or environmentally sustainable when practiced on a commercial scale. Likewise, average Y_P may be smaller than contest-winning yields because winning yields come from the most favourable combination of soil, weather, and crop management over a large geographic area. For example, Grassini *et al.* (2009) estimated average Y_P to range between 11.4-16.1 Mg ha^{-1} across 18 locations in the Western U.S. Corn Belt based on simulation modelling using 20 years of weather records and site-specific management. Hence, the magnitude of the exploitable yield gap has not been accurately quantified based on the current management of maize systems.

Lack of data from well-design experiments in which yield-limiting factors have been effectively controlled makes it difficult to obtain reliable quantifications of Y_P based on actual measurements (Duvick and Cassman, 1999). Simulation models can provide reasonable estimates of Y_P when soil and historical daily weather data are available (Abeledo *et al.*, 2008; Lobell *et al.*, 2009). Data collected from famers' fields can be used to evaluate actual productivity and identify major limitations in crop systems (*e.g.*, Mercau *et al.*, 2001; Sadras *et al.*, 2002; Lobell *et al.*, 2005). Because these studies lack an explicit experimental design and specific hypotheses, it difficult to establish causal relationships although sensitive factors associated with productivity can be identified (Wiese, 1982; Sadras *et al.*, 2002).

Given the paucity of measured data that can benchmark average farm yields against Y_P, we explored the use of on-farm crop yield and management data with simulation modelling to assess actual and potential productivity of high-yield irrigated maize systems. Specific objectives of the present study were to (i) provide a description of current management practices in irrigated maize systems using a large database collected from farmers' fields in central Nebraska (USA), (ii) quantify the existing gap between actual yield and Y_P using on-farm data and simulation analysis, and (iii) assess the impact of agronomic practices on on-farm yield and Y_P.

4.2. MATERIALS AND METHODS

4.2.1. Tri-Basin Natural Resources District (NRD)

State law divides Nebraska into 23 natural resources districts (NRDs), each serving as a local government entity with authority to establish regulations and incentives to protect and conserve natural resources within the district (http://www.nrdnet.org/). Each NRD sets its own priorities and develops its own programs to best serve local needs. The Tri-Basin NRD (http://www.tribasinnrd.org/) includes Gosper, Phelps, and Kearney counties in central Nebraska (Fig. 4-1). Total cropland area (excluding crops for silage and forages) in these three counties is approximately 250,000 ha (USDA-NASS, 2001-2008). Major crops are maize and soybean (61 and 33% of total cropland area, respectively); 87 and 90% of the land area planted with these crops, respectively, is under irrigation. There are 6,176 active registered groundwater wells for agricultural use in the area (Nebraska DNR, 2009). Average rainfed yields for maize and soybean in the Tri-Basin NRD three-county region are 5.2 and 2.2 Mg ha^{-1}, respectively, and 12.1 and 3.9 Mg ha^{-1} with irrigation (USDA-NASS, 2001-2008). Average maize yield with irrigation is similar to the Nebraska state-level irrigated average yield (11.9 Mg ha^{-1}). Maize production in the Tri-Basin NRD (≈ 1.7 million Mg) is highly dependant on irrigated maize, which represents 94% of total production.

The area inside the Tri-Basin NRD has flat to rolling terrain. Soils suitable for maize production are mapped in the Holdrege and, to a lesser extent, the Coly, Detroit, Hobbs, Kenesaw, and Uly series (USDA-NRCS). All series have silt loam texture. Available soil water-holding capacity in the root zone (0-1.5 m) ranges from 230 to 320 mm. None of the soils have physical impediments to root growth under typical production conditions. Annual patterns of radiation, temperature, rainfall, and crop evapotranspiration (ET_C) in Tri-Basin NRD are shown in Fig. 4-2. Rainfall distribution follows a monsoonal pattern: 70% is concentrated in the maize growing season. ET_C peaks in July and August, which is coincident with silking and early grain-filling crop stages. Total water deficit, estimated as difference between rainfall and ET_C during growing season is 253 ± 47 mm, well above the water deficit estimated for other more favorable locations in U.S. Corn Belt such as Ames, Iowa (32 ± 44 mm). Hence, maize crops grown in Tri-Basin NRD depend strongly on irrigation water and stored soil moisture that accumulates from snow melt and spring rains.

4.2.2. Database description and analysis

Farmers in the Tri-Basin NRD must report data on certain management practices used on each of their irrigated fields. Included in this NRD database are geographic coordinates, grain yield (at standard moisture content of 0.155 kg H_2O kg^{-1} grain), previous crop, and amount of nitrogen (N) fertilizer applied. There are three basins within the Tri-Basin NRD: Little Blue, Platte, and Republican. Farmers in the Republican Basin must also report the type of irrigation system and amount of irrigation water applied during crop growing-season based on flow meter readings. For the current study, we used data from 521 commercial irrigated maize fields (mean size: 46 ha) in the Republican Basin from 2005-2007 (Fig. 4-1). Some fields were included in more than one year, so our analysis included a total of 777 field-year observations. Each field was planted, managed, and (mechanically) harvested as a unit.

Data on crop management (sowing date, seeding rate, hybrid name and relative maturity [RM][4], and tillage system) and adversities (incidence of insects, pests, diseases, hail, lodging, green snap, and lack of stand uniformity) were collected from a subset of 123 field-years through mail survey, phone, and personal interviews (Fig. 4-1). Incidence of crop adversities was based on farmers' visual inspection and records. Two-tailed t-tests were performed separately for each year and showed no difference in grain yield, applied irrigation, or rate of N fertilizer between the 777 field-year database and the subset of 123 field-years ($p > 0.20$), except in 2006 when yield in the subset was slightly higher (3%, $p = 0.04$) than in the complete database. Thus, similarity in yield and applied inputs indicate the 123 field-year subset is representative of the larger database.

A variety of analytical methods are available to describe and analyze on-farm data as reviewed by Wiese (1982). In the present study, frequency distributions were calculated to illustrate the range of variation and probabilities associated with actual yield and crop

[4] Relative maturity values are reported by seed companies for each hybrid on the market.

management practices. Two approaches were used to assess causes of yield variation due to management factors: (i) regression analysis and (ii) comparison of factors means measured in the highest- *vs.* lowest-yielding field classes (determined from the upper and lower yield terciles, respectively, on each year) using a two-tailed t-test or Wilcoxon test when distribution of observed values deviated from normality. To investigate interactions between sowing date and hybrid maturity, crops were classified into four sowing date interval categories (day of year [DOY] 105-113, 114-120, 121-127, and 128-135) and two RM categories ('short'- [RM 106-112 d] and 'full-season' hybrids [RM 113-118 d]). Short- and full-season hybrids were equally represented across the four sowing intervals.

4.2.3. Simulation analysis

The Hybrid-Maize model (Yang *et al.*, 2004, 2006) was used to simulate Y_P for the subset of crops that included data on actual sowing date, hybrid brand and RM, and seeding rate (n = 123). Hybrid-Maize is a process-oriented model that simulates maize development and growth on a daily time-step under growth conditions without limitations from nutrient deficiencies or toxicities, or from insect pests, diseases, and weeds. It features temperature-driven maize development, vertical canopy integration of photosynthesis, organ-specific growth respiration, and temperature-sensitive maintenance respiration. Validation of Hybrid-Maize has shown to be robust and reasonable accurate in estimating maize yields in field studies across a wide range of environments in the U.S. Corn Belt where the crop was managed under near optimal conditions (Grassini *et. al.*, 2009). Daily values of radiation and maximum and minimum temperature are required to simulate Y_P with this model. Thus, synthetic weather files were assembled for each of the 123 field-years with data on crop management. A *modified inverse distance weight method* proposed by Franke and Nielson (1980) was used to interpolate daily values of incident solar radiation and maximum and minimum temperature from meteorological stations located inside or near the Tri-Basin NRD (n = 8; Fig. 4-1). Density and distribution of meteorological stations were adequate to describe geospatial patterns of radiation and temperature (Hubbard, 1994). Simulations used actual sowing date, hybrid brand and RM, and plant population reported for each field-year observation. Hybrid-Maize requires effective plant population density, thus, the latter was assumed to be 94% of actual seeding rate as suggested by Yang *et al.* (2006). Yield gap for each field-year was calculated as the difference between actual reported yield from the NRD database and simulated Y_P.

Opportunities to increase Y_P by changing current crop management were investigated using Hybrid-Maize in combination with daily radiation and temperature records from four meteorological stations inside or near the Tri-Basin NRD. One weather station (Holdrege) had weather records from the 1988-2008 period; the other three weather stations (Holdrege 4N, Minden and Smithfield) had records from the 1996-2008 period (Fig. 4-1). Change in mean Y_P at Holdrege when simulations used weather records from the 1988-2008 instead of 1996-2008 interval was negligible (< 0.5%); thus, Y_P at Holdrege was estimated using 1988-2008 weather record series. A representative combination of current average farmer management practices from the subset of 123 field-year observations (sowing date: DOY 117, RM 113 d, 7.2 plants m^{-2}) was taken as a baseline to evaluate Y_P response to changes in sowing date (-7, +7, and +14 d), RM (-4 and +4 d), and plant population (+0.7, +1.4 plants m^{-2}) resulting in 36 sowing date x RM x plant population combinations. Sign and magnitude of these changes were representative of the actual range of management practices used by farmers in the 123 field-year subset. Average Y_P for each of the 36 combinations was calculated by averaging the mean Y_P calculated using weather records from the four weather stations. Additionally, time trends in Tri-Basin NRD (3-county average) irrigated yields reported by NASS-USDA were compared against average Y_P simulated for the 1988-2008 period using current average farmer management practices (sowing date: DOY 117, RM 113 d, 7.2 plants m^{-2}).

4.3. RESULTS

4.3.1. Actual productivity and management of irrigated maize systems in central Nebraska

Farmer's grain yields were normally distributed and had a relatively small degree of variation for production-scale data, which attest to both the high degree of farmer management skills and the favorable environment for irrigated maize production (Fig. 4-3a). Mean 3-y yield was slightly above (≈ 5%) the Tri-Basin 3-county irrigated average yield (12.3 Mg ha^{-1}; USDA-NASS, 2005-2007). The effect of year on grain yield was significant ($p < 0.001$): average and maximum yields were lower in 2006 and 2007 compared with those reported in 2005. This reduction in yield was presumably due to an episode of very high temperature and low relative humidity immediately after silking in

2006 (data not shown) and higher night temperatures combined with low radiation during the post-silking phase in 2007 (Table 4-1; see also Section 4.3.3). No geospatial pattern in grain yield was observed in any of the years (data not shown).

Frequency distribution of applied irrigation deviated from normality because 15 to 20% of the fields in each year received a much larger amount of applied water than other fields (Fig. 4-3b). Effect of year on irrigation was significant ($p < 0.001$). Average applied irrigation decreased from 2005 to 2007, and this trend was associated with higher rainfall and lower evaporative demand during the silking and post-silking phases (Table 4-1). Irrigation was applied by center pivot sprinklers, surface gravity (mostly gated-piped furrows), or a combination of both irrigation systems (49, 33, and 18% of the total fields, respectively). The latter category involves a center pivot that typically covers >85% of total field area coupled with surface irrigation in field corners. Main energy sources for irrigation systems are natural gas, diesel, and electricity (49, 26, and 21%, respectively). Most farmers (≈ 70-75%) rely on crop consultants to determine amount and timing of irrigation events. Irrigations are typically scheduled based on soil water content, water balance computations, and type of irrigation system. A thorough analysis of irrigation management and efficiency is discussed in a separate paper (Grassini *et al.*, 2010).

Average rates of N fertilizer in the Tri-Basin NRD dataset did not differ among years or irrigation system ($p = 0.66$; Fig. 4-3c). Mean N fertilizer rate in maize grown after soybean was 21 kg N ha^{-1} less than when maize followed maize ($p < 0.001$) while N rates were similar across tillage systems ($p > 0.40$). Most N fertilizer was incorporated before sowing (70-90%); the rest was applied as a side-dressing or fertigation during the crop growing season. Over the last 10 years, anhydrous ammonia has been gradually replaced by urea-ammonium-nitrate solution (UAN), and these two forms account for approximately 70-80% of total N fertilizer applied in commercial maize fields in the Tri-Basin NRD (USDA-NASS, 1999-2008). Although mean N rate on irrigated maize in the Tri-Basin was considerably greater than the Nebraska state average (182 *vs.* 152 kg N ha^{-1}), N fertilizer use efficiency (kg grain per kg N fertilizer applied) was also much higher than Nebraska state average (71 *vs.* 64 kg grain kg^{-1} N fertilizer).

Sources of indigenous N supply include residual soil inorganic N, net N mineralization from soil organic matter and residues, and N inputs from atmospheric deposition and irrigation water. Based on measured plant N accumulation in replicated on-farm plots that did not receive N fertilizer, the contribution of indigenous N supply to irrigated maize in Tri-Basin NRD is about 145 kg N ha^{-1}, as measured in the study of Dobermann *et al.* (2006), which is consistent with values of indigenous N supply reported for U.S. Corn Belt (Cassman *et al.*, 2002). Average N fertilizer uptake efficiency, calculated as the ratio of (N accumulation at farmers average yield level minus N uptake in non-fertilized plots) to applied N fertilizer, is 0.40 kg N uptake per kg N supply. In the previous calculation, N accumulation in aboveground biomass for average yield reported by farmers in this study (13.0 Mg ha^{-1}) was derived from the generic relationship between maize grain yield and N uptake following Cassman *et al.* (2002). Phosphorous (P) fertilizer is typically applied before planting at a rate of about 25 kg P ha^{-1}. Potassium fertilizer is rarely applied to maize in the Tri-Basin NRD because soil tests usually indicate adequate supply of this nutrient.

Most common crop sequences were maize after soybean and continuous maize (61 and 38%, respectively). A small proportion of maize (1%) was sown after wheat. No-till, ridge-till, disk, and strip-till accounted for 37, 31, 22, and 10% of the crops, respectively. Crop sequences and tillage systems were equally represented across years. Data on sowing date, RM and seeding rate collected from a subset of 123 field-years are summarized in Figs. 3d, e, f. Frequency distributions for these parameters did not deviate from normality except for seeding rate. While RM and seeding rates were not different across years ($p > 0.80$), maize sowing in 2007 was later than in 2005 and 2006 (DOY 123 vs. 114 and 115, respectively) due to intense rainfall between DOY 112 and DOY 115.

4.3.2. Impact of management practices on actual yield

Crop sequence and tillage system have significant effects on grain yield ($p < 0.001$). Data contained in the 777 field-year database revealed that maize after soybean produced 0.5 ± 0.1 Mg ha^{-1} more than maize after maize, which was consistent across years (Fig. 4-4a). The subset of fields with more detailed management indicated a significant crop sequence x tillage interaction on grain yield ($p < 0.005$): while yield was not affected by tillage when maize followed soybean, maize yield following maize was smaller in ridge- and no-till compared to disk (Fig. 4-4b). Yield advantage of maize/soybean rotation over continuous maize was only significant in no-tilled crops.

Regression analysis and two-tailed t-test comparison of highest- and lowest-yield field classes showed a significant effect of sowing date, seeding rate, and in a lesser degree, RM on actual yields (Table 4-2). In general, highest-yield fields were observed with early sowing (DOY 107 to 120) and high seeding rates (> 7.5 seeds m^{-2}). A small advantage of full- over short-season hybrids (≈ 0.3 Mg ha^{-1}) was consistent in the first three sowing intervals (DOY 105 to 127). This trend reversed (-0.2 Mg ha^{-1}) in the last interval (DOY 128-135) probably due to greater incidence of a frost event before physiological maturity in full-season hybrids. Data analysis also revealed that yield was poorly related to the rate of N fertilizer and amount of applied irrigation. Although frequency of fields reported by farmers to have been affected by diseases, weeds, insects, hail damage, lodging, green snap or lack of stand uniformity was not negligible (10, 15, and 25% in 2005, 2006, and 2007 seasons, respectively), there was no correlation between incidence of these constraints and yield. We suspect that farmers reported these occurrences even when a relatively small portion of the field was affected.

4.3.3. Yield gaps and opportunities for increasing yield potential through crop management

There was a significant effect of year ($p < 0.001$) on simulated Y_P, yield gap, and the ratio of actual yield to Y_P (Fig. 4-5a, b, c). Average Y_P in 2007 (14.2 Mg ha^{-1}) was lower than in 2005 and 2006 (15.3 and 15.1 Mg ha^{-1}, respectively). The late sowing date in 2007 exposed crops to low solar radiation during the post-silking phase which, combined with high night temperatures that shortened the grain-filling period, reduced Y_P (Table 4-1). Management practices identified to affect Y_P were sowing date, RM, and seeding rate, which as independent variables in a multiple regression model explained 57, 81, and 54%

of the variation on Y_P in 2005, 2006, and 2007, respectively (data not shown). Sensitivity of simulated Y_P to these factors highlights the need for accurate specification of planting date, plant population, and cultivar maturity to arrive at Y_P estimates that reflect current crop management.

Yield gaps averaged -1.7 Mg ha^{-1} across years. Interestingly, yield gaps (expressed either as absolute values or percentage of Y_P) were more closely correlated to Y_P than actual yields ($p < 0.001$, $r^2 = 0.46$ and 0.26, respectively). Average on-farm yield in the Tri-Basin NRD was 89% of the Y_P simulated using current management practices. Yield potential simulated for the 1986-2008 period using current average farmer management practices and actual weather records in each year averaged 15.4 ± 0.3 Mg ha^{-1} (Fig. 4-6). No time trend in simulated Y_P was detected. Actual mean irrigated yield in the Tri-Basin NRD increased at 135 kg ha^{-1} y^{-1} during the 1970-2008 period. However, no increase in actual yield has occurred during the last 8-y period of the time series, a period in which farmers' yields have remained relatively stable at 21% below simulated Y_P (mean: 12.1 ± 0.1 Mg ha^{-1}). This estimate of yield gap contrasts with the value derived from simulation analysis using field-year specific data (21 *versus* 11%, respectively). We speculate the reasons for this difference were due to (i) *specific management practices* were used to determine Y_P for the subset of 123 field-years while *average management practices* were used to estimate Tri-Basin NRD 3-county average Y_P; (ii) 100 out of the 123 field-years included in our subset were located in Phelps County, which has a higher average irrigated yield (+0.4 Mg ha^{-1}) than reported for Gosper and Kearney Counties; and (iii) average yield gap derived from Fig. 4-6 for the 2005-2007 period was slightly smaller than the 2001-2008 average (18 *versus* 21% of Y_P, respectively).

Changes in current management practices were explored as an option to increase the Y_P ceiling. Simulations using long-term weather records from four meteorological stations inside or near the area of study showed increases in Y_P with higher plant population and longer hybrid RM while sowing date effect was relatively small (Table 4-3). Compared to average current management practices (sowing date: DOY 117, RM 113 d, 7.2 plants m^{-2}), Y_P increased by 6 and 8% when RM was extended to 117 d and plant population increased to 8.6 plants m^{-2}, respectively, and by 13% when both RM and plant population were increased (mean: 17.5 ± 0.44 Mg ha^{-1}; see dashed horizontal line in Fig. 4-6). Using 117 d RM and 8.6 plants m^{-2} as the reference scenario for simulated maximum Y_P, Tri-Basin NRD 3-county average irrigated yields (2001-2008) are 70% of this benchmark. While extending growth duration through use of a longer maturity hybrid gives higher simulated Y_P, it also substantially increases the risk of frost occurrence before physiological maturity (Table 4-3).

4.4. DISCUSSION

The use of on-farm data to identify major management constraints to actual productivity has strengths and weaknesses. A major weakness is that uncontrolled factors across farms can confound effects of management practices on yield. Such confounding can be minimized or avoided if data used in the analysis are of sufficient detail and quality, and include a representative population of farmers over several cropping seasons. These requirements appear to be met by the Tri-Basin NRD database used in the present study. As both federal and state governments increase regulatory pressures on environmental performance of agriculture (*e.g.*, water quality, endangered species, and greenhouse gas emissions), farm reporting requirements for factors affecting environmental performance will likely increase. The result will be greater availability of high quality on-farm data, which provides opportunities to quantify the impact of management practices on yield and efficiencies of water and fertilizer as a compliment to high-cost, multi-year, multi-site field studies.

This study evaluated the impact of current management practices on yield in high-yield irrigated maize systems where actual yields approach Y_P. Rotation, tillage system, sowing date, and plant population density were identified as most sensitive factors affecting current yields. The effect of rotation and tillage system on yield of irrigated maize reported here are consistent with published data from long-term rainfed field experiments (Porter *et al.*, 1997; Fischer *et al.*, 2002; Boomsma *et al.*, 2010). While yield of maize after soybean had an overall advantage compared to maize after maize, the benefit of rotation was greater in fields under conservation tillage. Whereas rotation and tillage effects on rainfed yields have multiple causes, including residual N, soil water storage, and disease pressure (Kirkegaard *et al.*, 2008), there is no explanation for such effects on yield of irrigated maize that receives adequate supplies of nutrients and water and most yield-reducing factors are effectively controlled (Verma *et al.*, 2005).

Farmers in the Tri-Basin NRD had grain yields that were ~35% greater than Nebraska state average yield, which includes both irrigated and rainfed production. Although they used 20% higher N fertilizer rates, N-fertilizer efficiency was 11% greater than the state average. Extension education in the Tri-Basin NRD encourages use of N 'credits' for manure, legume rotations, nitrates applied in irrigation water, and residual soil nitrate as determined by soil testing. As a result, 66% of reported N-fertilizer rates were within ±20% recommended values (data not shown). The results also suggest that Tri-Basin farmers can further improve N fertilizer efficiency by achieving better congruence between nitrogen supply and crop N demand. For example, shifting N application from fall to spring or at planting and greater use of split N-fertilizer or fertigation applications during the growing season, rather than a single large N application, represent options to achieve better congruence (Cassman *et al.*, 2002).

Time trends in Y_P and actual yield in the Tri-Basin NRD suggest that size of exploitable yield gap for irrigated maize has decreased markedly as average yields are now about 80% of the Y_P ceiling. Moreover, lack of increase in actual yield since 2001 may represent first indications of a plateau in actual yields as it has been reported for irrigated rice systems in Asia (Cassman *et al.*, 2003). The fact that magnitude of the yield gap in a given year was more closely correlated with Y_P than actual yield suggests that current management practices, focused on maximizing net return, may limit productivity in years when weather conditions support Y_P levels above the long-term average.

The average yield gap reported in this study for irrigated maize in the Tri-Basin NRD based on field-specific management is smaller than Nebraska state-level gap estimated by Duvick and Cassman (1999). This apparent discrepancy is due to differences in the method used to estimate current average Y_P. Whereas Duvick and Cassman used contest-winning yields as the Y_P reference, the current study used simulations based on actual weather and management data for a large number of field-year observations. The latter accounts for a more representative spectrum of current management practices, soil quality, and weather conditions in estimates of Y_P for farmers' who seek to maximize net return. In contrast, contest-winning yields provide an estimate of the single best combination of management and environment amongst a large number of competing farmers and environments, which is not representative of average Y_P at regional, state, or national scales. Consistent with this discrepancy is the observation that Nebraska contest-winning average irrigated yield reported by Duvick and Cassman (1999) compares well with maximum simulated Y_P estimated in our study using a combination of practices that gives highest Y_P (18.2 *vs.* 17.5 Mg ha^{-1}).

Results from this study suggest limited potential for further increases in irrigated maize yields without a substantial increase in the current Y_P ceiling. While some of the yield constraints are not amenable to improved management (*e.g.*, excessive heat, terminal frost, warm nighttime temperatures), actual yields may be increased through incremental changes in crop management (*e.g.*, earlier planting dates, soybean-maize rotation instead of continuous maize). Other options might increase Y_P but are operationally difficult or economically risky to adopt (*e.g.*, higher plant population and longer maturity). Whilst improving irrigation and nutrient management may reduce excessive inputs amounts and protect environmental quality by enhancing input efficiency, they will have little impact on yield. The same applies to transgenic approaches for higher nitrogen- or water-use efficiencies. Instead, improvement in maize yielding ability is most likely to occur by continued brute-force breeding for grain yield and yield stability across a wide range of environments to produce a continuous stream of improved hybrids, complemented by agronomic research to more fully exploit crop community-level relations and genotype by environment interactions in high-yield environments (Duvick and Cassman, 1999, Denison, 2007).

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Table 4-1. Average (±SE) total incoming solar radiation, maximum (T_{max}) and minimum (T_{min}) temperatures, total rainfall, and total reference evapotranspiration (ET_O; FAO-Penman-Monteith) computed for the entire crop cycle (ECC), or the pre-silking (Pre-S), around-silking (S), and post-silking (Post-S) phases of maize crops grown in the Tri-Basin Natural Resources District (NRD) during the 2005-2007 seasons. 12-y means for the ECC are also shown.

Season	Crop phase [†]	Solar radiation (MJ m^{-2} d^{-1})	T_{max} (ºC)	T_{min} (ºC)	Rainfall (mm)	ET_O (mm)
2005	Pre-S	20.7 ± 0.3 [‡]	24.0 ± 0.2	10.5 ± 0.3	227 ± 6	448 ± 4
	S	23.2 ± 0.6	32.1 ± 0.5	17.9 ± 0.1	26 ±4	198 ± 9
	Post-S	20.1 ± 0.4	29.2 ± 0.3	15.6 ± 0.1	113 ± 9	259 ± 9
	ECC	21.0 ± 0.4	27.2 ± 0.3	13.6 ± 0.2	366 ± 13	906 ± 22
2006	Pre-S	23.4 ± 0.3	26.5 ± 0.1	11.2 ± 0.1	179 ± 14	510 ± 3
	S	24.2 ± 0.4	31.0 ± 0.2	17.1 ± 0.1	59 ± 9	189 ± 5
	Post-S	20.3 ± 0.5	29.1 ± 0.3	16.3 ± 0.1	148 ± 29	252 ± 9
	ECC	22.5 ± 0.4	28.2 ± 0.2	14.0 ± 0.1	386 ± 31	952 ± 15
2007	Pre-S	22.1 ± 0.5	25.2 ± 0.1	13.0 ± 0.2	225 ± 23	377 ± 1
	S	23.8 ± 0.4	30.8 ± 0.4	17.6 ± 0.2	53 ± 13	175 ± 7
	Post-S	19.2 ± 0.4	30.1 ± 0.3	18.2 ± 0.1	153 ± 12	227 ± 11
	ECC	21.5 ± 0.4	28.0 ± 0.2	15.7 ± 0.2	431 ± 27	779 ± 17
12-y mean	ECC	20.8 ± 0.2	27.4 ± 0.3	13.9 ± 0.1	392 ± 12	907 ± 16

[†] Crop phases for each year were determined based on average actual sowing date and simulated dates of silking and maturity for a 113-d RM hybrid using Hybrid-Maize model.

[‡] Each value is the average of four weather stations inside or near the Tri-Basin NRD (Holdrege, Holdrege 4N, Minden, and Smithfield).

Table 4-2. Coefficients (±SE) of linear regressions between actual yield (Mg ha^{-1}) and a series of management factors. Data were pooled across years. Quadratic effects were not significant. Factors means for lowest- (LY) and highest-yield fields (HY) are also shown (average yield: 12.1 and 13.9 Mg ha^{-1}, respectively); the difference (Δ) was tested by a two-tailed t-test or Wilcoxon test when distribution deviated from normality.

Management factor	Intercept	Slope	Pearson *r*	Factors means		
				LY [†]	HY [†]	Δ
Planting date (day of year)	17.1 ± 1.3	-0.03 ± 0.01	-0.32**	119	115	4**
Hybrid relative maturity (days)	5.9 ± 3.8	0.06 ± 0.03	0.17*	112	114	2*
Seeding rate (m^{-2})	8.2 ± 1.6	0.65 ± 0.21	0.32**	7.4	7.7	0.3***
N fertilizer rate (kg N ha^{-1})	14.1 ± 0.5	-0.005 ± 0.003	0.15	187	182	5
Applied irrigation (mm)	12.7 ± 0.2	0.001 ± 0.001	0.26*	224	271	47

[†] Lowest- and highest-yield categories based on pooling fields in the lower and upper tercile of the yield frequency distribution across years, respectively. Asterisks indicate significance at * $p<0.05$, ** $p<0.01$, and *** $p<0.001$.

Table 4-3. Simulated yield potential (Y_P) using long-term weather records under different combinations of hybrid relative maturity, plant population density, and sowing date. Average Y_P for current average farmer management practices in the Tri-Basin Natural Resources District (NRD) is underlined. Percentage of years in which frost occurs before physiological maturity is indicated between brackets for each of the relative maturity x sowing date combinations.

Relative maturity (d)	Plant population (m^{-2})	Sowing date (day of year)			
		110	117	124	131
109	7.2	14.3 † (5)	14.4 (5)	14.5 (5)	14.5 (14)
	7.9	14.9	14.9	15.1	15.1
	8.6	15.4	15.4	15.6	15.7
113	7.2	15.3 (10)	<u>15.4 (14)</u>	15.4 (14)	15.5 (19)
	7.9	15.9	16.0	16.1	16.2
	8.6	16.5	16.6	16.6	16.7
117	7.2	16.3 (14)	16.3 (24)	16.4 (29)	16.4 (33)
	7.9	16.9	16.9	17.0	17.0
	8.6	17.4	17.4	17.5	17.5

† Each value is the average of Y_P simulated in four locations inside or near the Tri-Basin NRD.

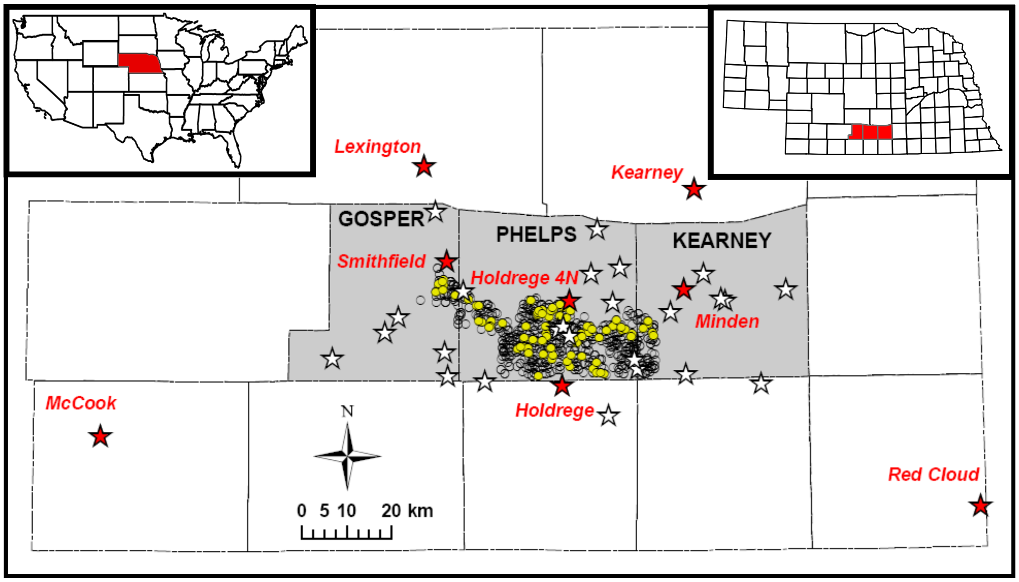

Figure 4-1. Map of south-central Nebraska showing the location of the Tri-Basin Natural Resources District (NRD; shaded area). Empty circles indicate location of the 521 fields included on the database; solid circles show location of those fields with additional data on crop management. Stars indicate location of rain gauges (n = 33); solid stars indicate location of meteorological stations used for interpolation of daily incident solar radiation, temperature, relative humidity, and reference evapotranspiration (n = 8; names are shown in italic). Lines show county boundaries; Tri-Basin NRD counties are named. Location of Tri-Basin NRD within Nebraska and Nebraska within contiguous U.S. is shown (right and left insets, respectively).

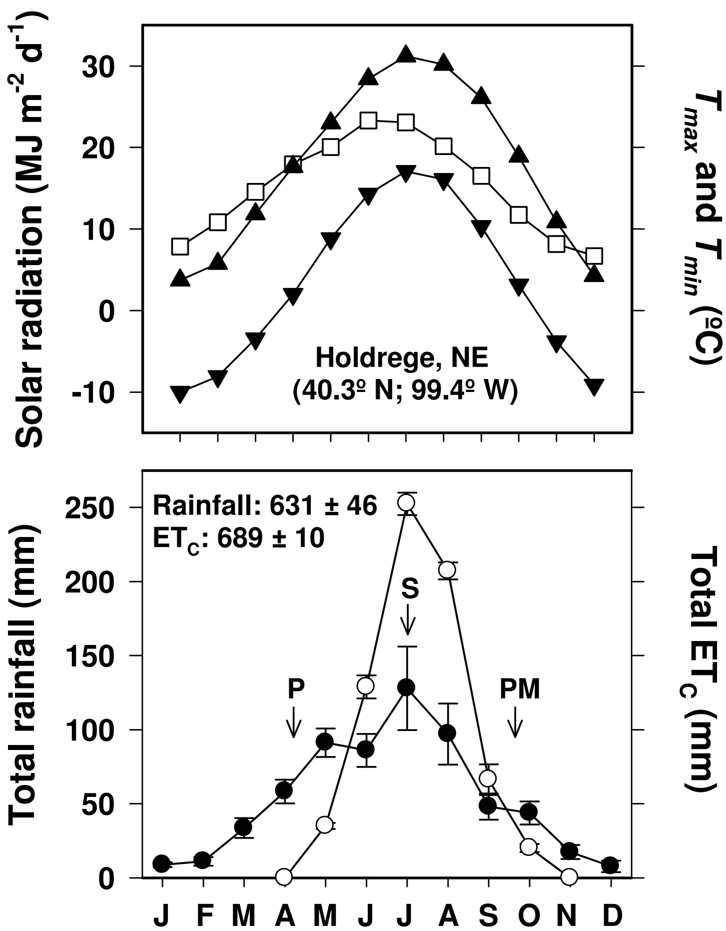

Figure 4-2. Monthly values for average total incoming solar radiation (□), maximum and minimum temperature (T_{max} [▲] and T_{min} [▼], respectively), total rainfall (●), and crop evapotranspiration under non-limiting water supply (ET_C [○]) in Tri-Basin Natural Resources District based on 20-year (1988-2008) weather records from Holdrege (see Fig. 4-1). ET_C simulated using Hybrid-Maize model for maize crops with average management practices (sowing date: DOY 117; relative maturity: 113 d; 7.2 plants m^{-2}). Error bars indicate ±SE of the mean. Arrows in bottom panel indicate average dates of planting (P), silking (S), and physiological maturity (PM). Annual average (±SE) total rainfall and ET_C are shown.

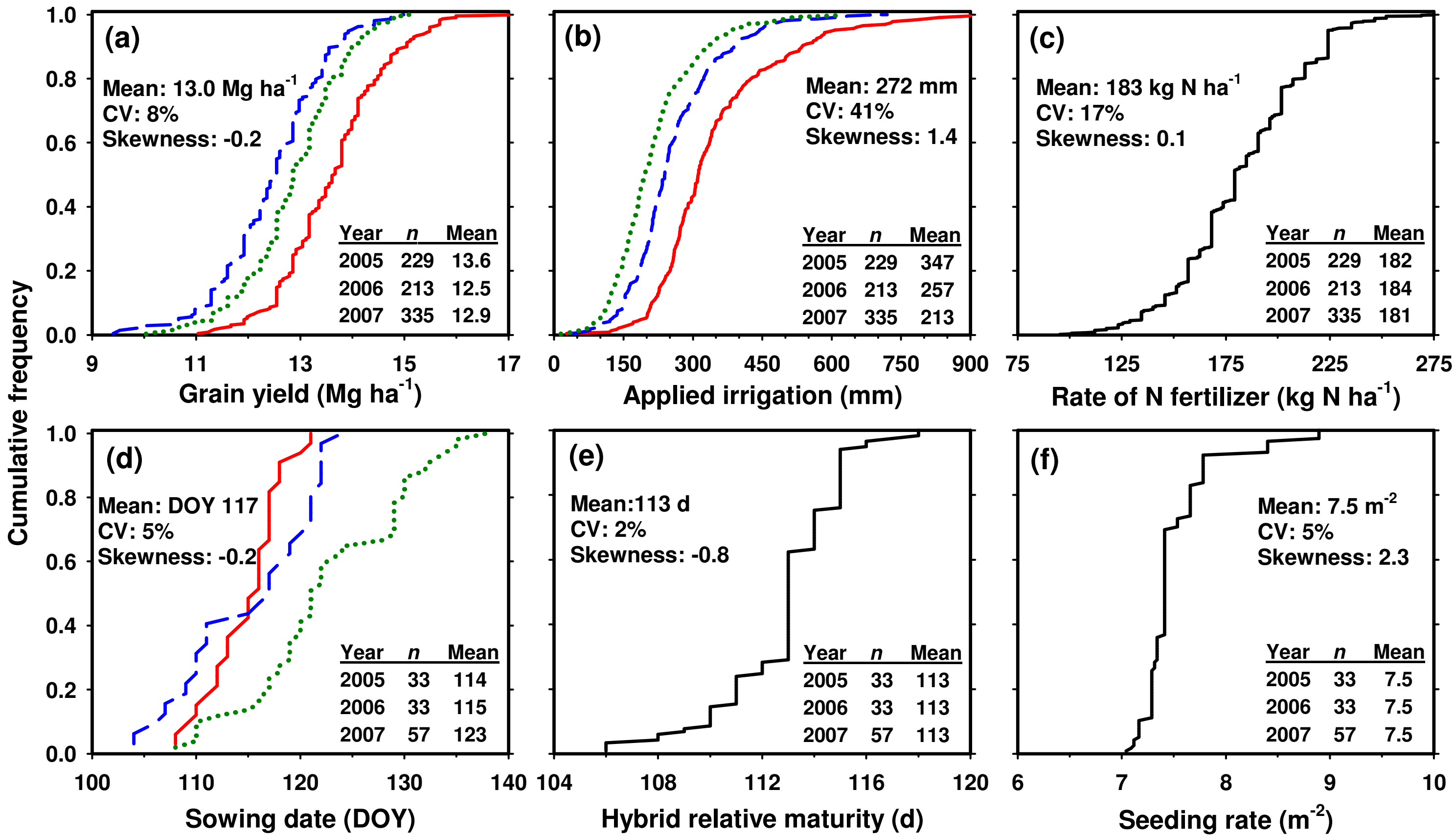

Figure 4-3. Cumulative frequency distributions of actual (a) grain yield, (b) applied irrigation, (c) rate of N fertilizer, (d) sowing date, (e) hybrid relative maturity, and (f) seeding rate collected from irrigated maize fields in the Tri-Basin Natural Resources District (NRD) during 2005 (—), 2006 (– –), and 2007 (- - -) seasons. Effect of year on rate of N fertilizer, hybrid maturity, and seeding rate was not significant ($p > 0.65$); thus, data were pooled across years. Mean values for each year are shown. Data for yield, irrigation, and N fertilizer rate came from the Tri-Basin NRD database with 777 field-year observations. Data for sowing date, hybrid maturity, and seeding rate were obtained from a subset of 123 field-year observations.

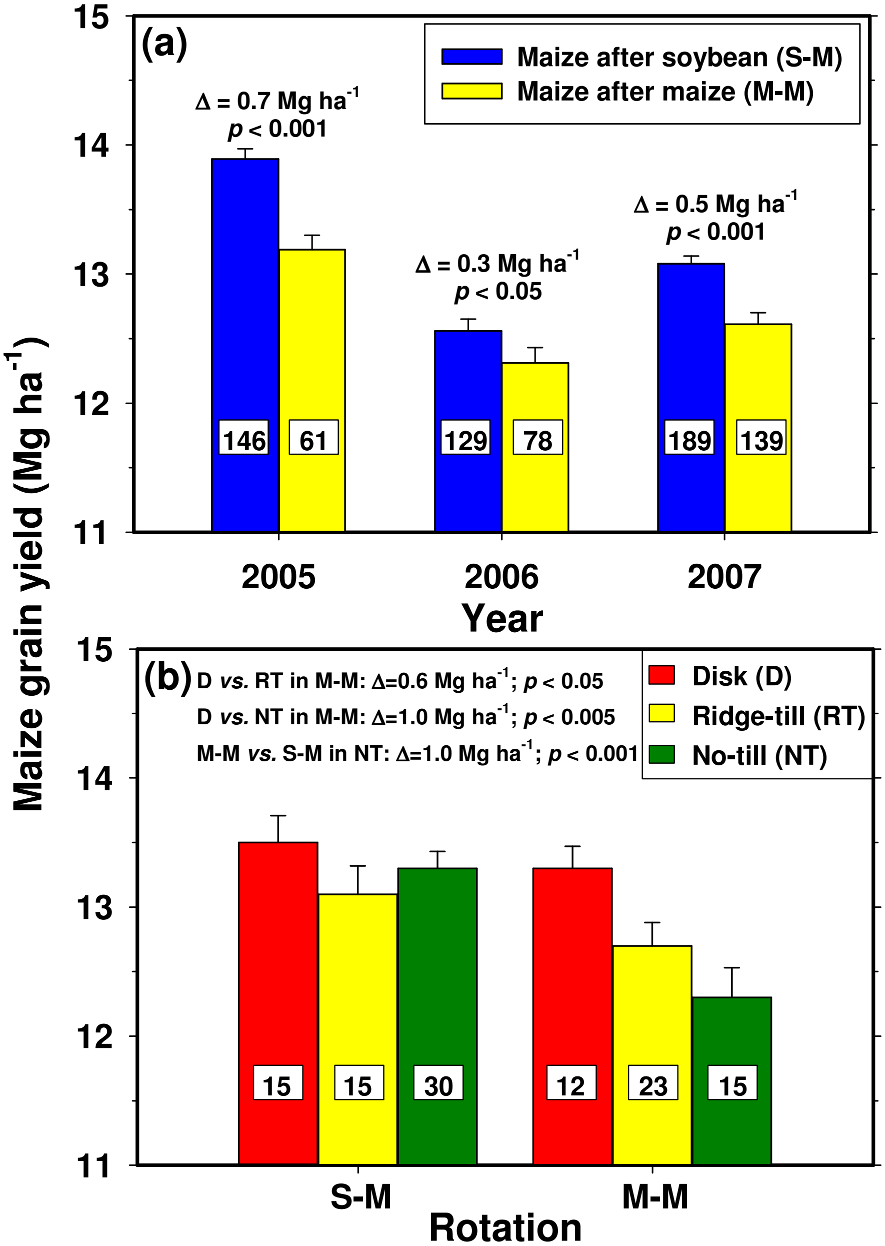

Figure 4-4. Average (±SE) maize yield in fields under different rotation (maize after maize and maize after soybean) during the 2005-2007 seasons (a) and under disk, ridge-, and no-till systems (b). Tillage systems were equally represented across years, thus, data were pooled across years in (b). Rotation x tillage interaction was significant ($p < 0.005$). Difference (Δ) and t-test significance for selected comparisons between rotations or tillage systems are shown. Numbers inside bars indicate number of observations. A small proportion of crops under strip-till or sown after wheat was not include in this analysis.

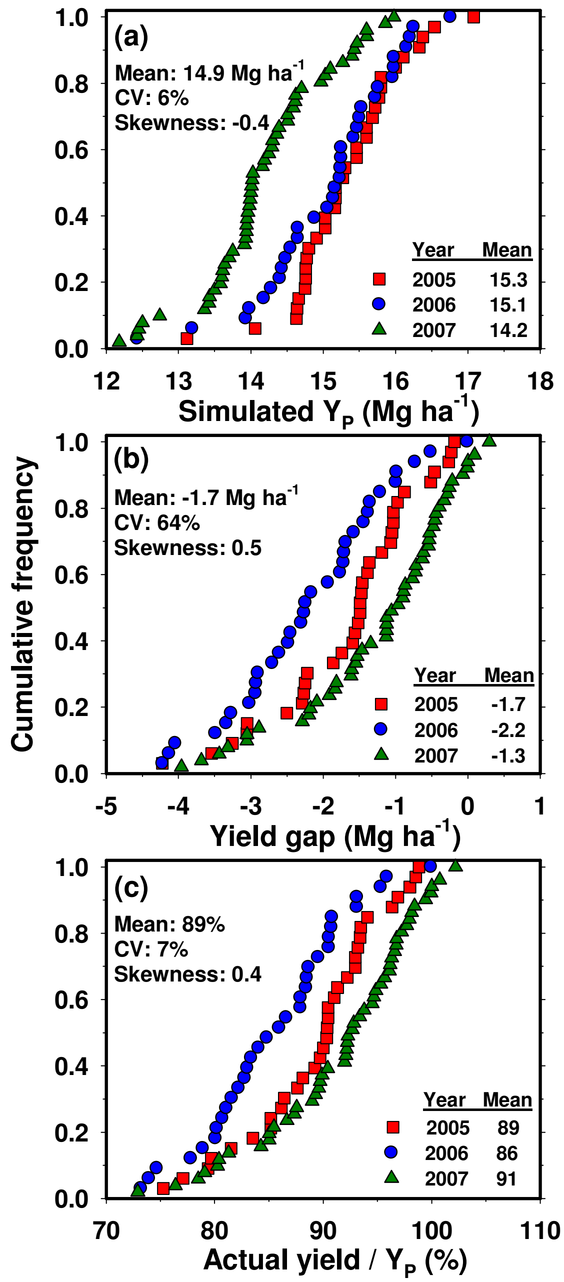

Figure 4-5. Cumulative frequency distributions of (a) yield potential [Y_P], (b) yield gap, and (c) actual yield as percentage of Y_P for a subset of maize crops grown in the Tri-Basin Natural Resources District (NRD) in 2005, 2006, and 2007 (n = 33, 33, and 57, respectively, representing a subset of 123 field-year observations for which detailed crop management data were obtained). Y_P was estimated using the Hybrid-Maize model in combination with actual weather records and management practices for each field. Yield gap was computed as the difference between actual yield and corresponding simulated Y_P. Variables means for each year are shown.

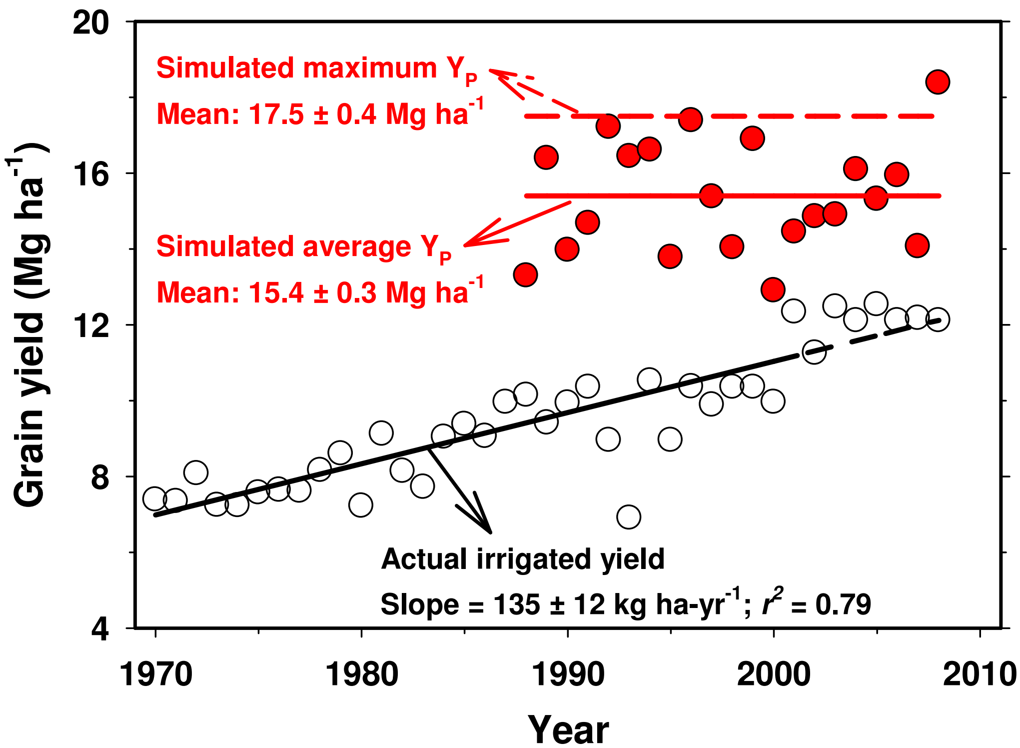

Figure 4-6. Trends in Tri-Basin NRD (3-county average) irrigated yields (○) and yield potential (Y_P, ●) simulated using Hybrid-Maize model based on average management practices and weather records (1988-2008). Dashed regression line for actual yield trend corresponds to lack of yield improvement in the last 8-y period. Upper dashed line is maximum simulated Y_P estimated based on the combination of practices that gives highest Y_P as given in Table 4-3. The slopes of the linear regressions for Y_P were undistinguishable from zero (p = 0.60).

CHAPTER 5: HIGH-YIELD IRRIGATED MAIZE IN WESTERN U.S. CORN BELT II. IRRIGATION MANAGEMENT AND CROP WATER PRODUCTIVITY [5]

ABSTRACT

Appropriate benchmarks for water productivity (WP), defined here as the amount of grain yield produced per unit of water supply, are needed to help identify and diagnose inefficiencies in crop production and water management in irrigated cropping systems. Such analysis is lacking for maize in the Western U.S. Corn Belt where irrigated production represents 58% of total maize output. In the present study, a benchmark for maize WP was (i) developed based on the relationships between simulated yield and seasonal water supply (stored soil water and sowing-to-maturity rainfall plus irrigation) documented in a previous study; (ii) validated against actual data from crops grown with good management over a wide range of environments and water supply regimes (n = 123); and (iii) used to evaluate WP of farmer's fields in central Nebraska using a 3-y database (2005-2007) that included field-specific values for yield and applied irrigation (n = 777). The database was also used to quantify applied irrigation, irrigation water-use efficiency (IWUE; amount of yield produced per unit of applied irrigation), and the impact of agronomic practices on both parameters. Opportunities for improving irrigation management were evaluated using a maize simulation model in combination with actual weather records and detailed data on soil properties and crop management collected from

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a subset of fields (n = 123). The linear function derived from the relationship between simulated grain yield and seasonal water supply, namely the *mean WP function* (slope = 19.3 kg ha^{-1} mm^{-1}; x-intercept = 100 mm), proved to be a robust benchmark for maize WP when compared with actual yield and water supply data. Average farmer's WP in central Nebraska was ~80% of the WP derived from the slope of the mean WP function. A substantial number of fields (55% of total) had water supply in excess of that required to achieve yield potential (900 mm). Pivot irrigation (instead of surface irrigation) and conservation tillage in fields under soybean-maize rotation had greatest IWUE and yield. Applied irrigation was 41 and 20% less under pivot and conservation tillage than under surface irrigation and conventional tillage, respectively, while yield was 4% greater with soybean-maize rotation than under continuous maize. Simulation analysis showed that up to 32% of the annual water volume allocated to irrigated maize in the region could be saved with little yield penalty, by switching current surface systems to pivot, improving irrigation schedules to be more synchronous with crop water requirements and, as a fine-tune option, adopting limited irrigation.

Keywords: *Zea Mays* L., maize, yield, irrigation, water productivity, irrigation water-use efficiency, simulation model.

Abbreviations: ASW_S: available soil water at sowing (mm); AWHC: available soil water-holding capacity (mm); CT: conventional tillage; ET_C: crop evapotranspiration (mm); ET_O: reference evapotranspiration (mm); IWUE: irrigation water use efficiency (kg grain mm^{-1} applied irrigation); NRD: Natural Resources District; NT: conservation tillage; RH: relative humidity (%): RM: hybrid-specific relative maturity (d), WP: water productivity (kg grain mm^{-1} water supply); Y_P: yield potential (Mg ha^{-1}).

5.1. INTRODUCTION

Agriculture is the largest user of freshwater accounting for about 75% of current withdrawals (Wallace, 2000; Howell, 2001). Food production from irrigated systems represents ~40% of the global total and uses only about 18% of the land area allocated to food production (Fereres and Connor, 2004). Rising demand for food, livestock feed, and biofuels coupled with global climate change will put increasing pressure on freshwater resources (Falkenmark *et al.*, 1998; Rosegrant *et al.*, 2009). Competition for scarce water is already evident in major irrigated cropping systems of the world (Postel, 1998; Perry *et al.*, 2009; Rosegrant *et al.*, 2009). Water productivity (WP) offers a quantifiable benchmark to assess crop production in relation to available water resources (Bouman *et al.*, 2005; Passioura, 2006). WP can be defined in several ways depending on the temporal and spatial scales of concern and study objectives. At the field level during a single crop growing season, WP can be quantified as the ratio of grain yield to either total crop transpiration, evapotranspiration (ET_C), or water supply (including available soil water at sowing plus sowing-to-maturity rainfall and irrigation). When data to derive actual ET_C are not available and the objective is to diagnose overall efficiency of the crop system with regard to total water inputs, WP expressed in terms of grain yield per unit of water supply is perhaps the most relevant parameter.

Boundary functions that define maximum attainable yield over a wide range of water supply have been used to benchmark on-farm WP and identify yield-limiting factors (*e.g.*, French and Shultz, 1984; Grassini *et al.*, 2009a). Major limitation of the boundary-function approach is not accounting for year-to-year variability in solar radiation, temperature, vapor pressure deficit, water supply distribution during the crop growing season, and water losses through soil evaporation, deep drainage, and unused water left in the ground at physiological maturity (Angus and van Herwaarden, 2001). Nevertheless, boundary-function benchmarks provide farmers and researchers a method to estimate realistic yield goals and water requirements, and to help identify management options to improve WP. Despite its potential, the benchmark approach has not yet been used to diagnose WP and irrigation management of irrigated maize.

In irrigated cropping systems, farmers tend to avoid risk by applying excessive amount of irrigation water in relation to crop water requirements to ensure maximum yield (Fereres and Gonzalez-Dugo, 2009). The low irrigation efficiency, decreasing access to irrigation water, and resulting negative environmental effects that result have motivated calls for new approaches to irrigation management (Taylor *et al.*, 1983; Loomis and Connor, 1992; Wallace *et al.*, 1997). Flexible irrigation schedules based on meteorological data, crop phenology, and soil water-holding capacity, coupled with soil and crop water status monitoring and weather forecasts, allow decreased irrigation water amounts with little or no yield penalties (Stewart and Nielsen, 1990; Loomis and Connor, 1992). A further refinement of this approach, called limited or deficit irrigation, consists of application of water below 100% replacement of ET_C requirements during crop stages that are not critical for yield determination (Pereira *et al.*, 2002; Fereres and Soriano, 2007). Simulation models can serve to evaluate actual irrigation management and to identify new approaches to improve irrigation efficiency in a given location when soil and historical daily weather data are available (Stöckle and James, 1989; Villalobos and Fereres, 1989).

This paper evaluates WP (kg grain ha^{-1} mm^{-1} water supply) and irrigation management of irrigated maize in the Western U.S. Corn Belt. Actual data from farmer's production fields and simulation analysis were combined to (i) establish a benchmark for maize WP in the Western U.S. Corn Belt, (ii) quantify WP in irrigated maize systems of central Nebraska, and (iii) identify opportunities to improve WP and irrigation management. This paper is complementary to a previous paper (Grassini *et al.*, submitted; see Chapter 4) that focused on the agronomic practices and nitrogen fertilizer efficiency of these same irrigated maize systems.

5.2. MATERIALS AND METHODS

5.2.1. Development and validation of a water productivity benchmark for maize

A re-analysis of simulated grain yield and water supply data (n = 1019) reported by Grassini *et al.* (2009b) was performed to establish a benchmark for on-farm WP. In this previous study, yield was simulated under rainfed and irrigated conditions at 18 locations across the Western U.S. Corn Belt using 20-y of weather data in combination with actual soil and crop management data. A *boundary function* was estimated for the relationship between attainable grain yield and water supply [slope = 27.7 kg ha^{-1} mm^{-1}; x-intercept (≈

seasonal soil evaporation) = 100 mm] over the range of water supply in which grain yield was responsive to increasing water availability. This boundary function defines the maximum attainable yield over a wide range of water supplies. A more relevant benchmark for crop producers is the *mean attainable WP function*, defined by the linear regression of simulated grain yield on water supply for all 1019 observations from the previous study. Outlier observations (< 3% of all observations) were identified and removed from the regression analysis using the method of Schabenberger and Pierce (2002).

Actual yields from field experiments that provided 123 treatment-site-years of data, including crops grown under rainfed and irrigated conditions, were used to evaluate whether the boundary and mean attainable WP functions can serve as benchmarks for maize WP (Table 5-1). This database included a wide range of environments and irrigation treatments, and maize was managed to avoid limitations from nutrient deficiencies, diseases, insect pests, and weeds. Rainfall and irrigation were recorded at each site. Available soil water at sowing (ASW_S) was reported in 33% of the site-years; for the rest, ASW_S was estimated by an empirical algorithm shown to be robust for estimating this parameter in the Western Corn Belt (Grassini *et al.*, 2010, see Section 5.2.2 for more details).

Throughout this manuscript, grain yields are reported at a standard moisture content of 0.155 kg H_2O kg^{-1} grain.

5.2.2. Quantification of water productivity in farmer's fields

A 3-y database (2005-2007) collected by staff in the Tri-Basin Natural Resources District (NRD) in central Nebraska was used to quantify maize WP and analyze irrigation management practices in farmers fields (n = 777). Maize production in the Tri-Basin NRD (≈ 1.7 million Mg) is highly dependant on irrigated maize, which represents 94% of total production (NASS-USDA, 2001-2008). There are three basins within the Tri-Basin NRD: Little Blue, Platte, and Republican. Flow meters are required on all wells in the Republican Basin portion of the district, which is the area included in our study. The database includes field-specific values for yield, previous crop, type of irrigation system, N fertilizer rate, and amount of applied irrigation. Each field included in the database was planted entirely with maize, and managed, and harvested as a unit. Irrigation systems represented in the database included center pivot sprinklers, surface gravity (mostly gated-pipe furrows), or a combination of both (49, 33, and 18% of the total fields, respectively). The latter category involves a center pivot that typically covers >85% of total field area coupled with surface irrigation in field corners. Because statistical analysis indicated that yield and amount of applied irrigation did not differ between fields with pivot or combined irrigation systems ($p > 0.60$ and $p > 0.15$, respectively), data from these two categories were pooled into a single "pivot" category. There were two kinds of center pivot sprinkler systems: (i) low-pressure sprinkler heads that hang near canopy level, and (ii) high-pressure sprinkler heads on the pivot beams well above the canopy. Average size of fields under pivot and surface systems was 53 and 32 ha, respectively. Main energy sources for irrigation pumping were natural gas, diesel, and electricity (49, 26, and 21% of total fields, respectively). Most farmers (≈ 70-75%) rely on crop consultants to determine amount and timing of irrigation events. Irrigations are typically scheduled based on soil water content, water balance computations, and type of irrigation system. Detailed site and database description are provided by Grassini *et al.* (submitted; see Chapter 4).

Seasonal water supply for each field-year observation was estimated as the sum of ASW_S in the rooting zone (0-1.5 m) plus sowing-to-maturity rainfall and applied irrigation. An empirical model that accounts for variations in non-growing season precipitation, residual soil water left by previous summer crop, and available water-holding capacity (AWHC) was used to estimate ASW_S (Grassini *et al.*, 2010). Non-growing season precipitation was calculated as total precipitation in the period from Oct 1st (approximate date by which crop canopy is completely senescent) and average actual sowing date in the following year. Residual water left in the soil profile by previous crop was assumed to be 60% of AWHC based on 20-y simulations of soil water dynamics performed for irrigated maize crops in Tri-Basin NRD area (Grassini *et al.*, 2009b). Based on field geographic coordinates and satellite images, AWHC was estimated from the SSURGO soil database (USDA-NRCS) for a zone (~380 m radius) centered on each field. Most fields were spatially homogeneous for soil type and AWHC; a weighted average was used to estimate AWHC in those fields that included soil types with different AWHC, but these were < 5% of total fields. Sowing-to-maturity rainfall was calculated as total rainfall between average actual sowing date and simulated date of physiological maturity for each site-year. Because rainfall exhibited very high spatial variability across the Tri-Basin NRD area, three weather station networks were used to ensure appropriate density and distribution of rain gauges (Automated Weather Station Network [AWDN, n = 8], National Weather Service Cooperative Station Network [NWS, n = 8], and

Nebraska Rainfall Assessment and Information Network [NeRAIN, n = 17] (see Fig. 4-1). A modified inverse distance weight method proposed by Franke and Nielson (1980) was used to interpolate daily rainfall values for each field during the 2004-2007 seasons.

For each field-year observation contained in the Tri-Basin NRD database, water productivity (WP) was calculated as the quotient of yield and seasonal water supply. Additionally, an estimate of WP for rainfed maize crops was calculated based on Tri-Basin NRD (3-county average) rainfed yields (USDA-NASS, 2005-2007) and estimated water supply without irrigation. For each year, irrigation water-use efficiency (IWUE) was calculated as the quotient of (i) yield and applied irrigation [IWUE(Y, I)] and (ii) the difference between irrigated yield minus Tri-Basin NRD average rainfed yield and applied irrigation [IWUE(ΔY, I)]. Calculation of ΔY seeks to minimize the effect of variability in rainfall and/or ASW_S on irrigation water-use efficiency across years (Howell, 2001). Variation in applied irrigation and IWUE(ΔY, I) were investigated using detailed data on crop management collected from a subset of 123 fields that include information on sowing date, seeding rate, hybrid relative maturity, and tillage system. Tillage systems included conventional disk tillage (CT) or conservation tillage under strip-, ridge-, or no-till practices. These three types of conservation tillage were combined into a single no-till category (NT) because yield and applied irrigation did not different among them ($p > 0.10$ for all t-test comparisons).

Regression analysis was performed to investigate relationships between applied irrigation amount, sowing-to-maturity rainfall, and ASW_S. Two approaches were used to assess causes of variation on applied irrigation due to management practices: (i) regression analysis and (ii) two-tailed t-test or Wilcoxon test when distribution of observed values deviated from normality. Management practices included in this analysis were: type of irrigation and tillage system, previous crop, rate of N fertilizer, seeding rate, sowing date, and hybrid relative maturity. Since the amount of applied irrigation differed among years ($p < 0.001$), the statistical analysis was performed separately for each year.

5.2.3. Simulation analysis of water productivity and irrigation management

Hybrid-Maize model (Yang *et al.*, 2004, 2006) was used to simulate yield and irrigation requirements for each of the 123 fields in the Tri-Basin NRD database subset using actual weather records, soil properties, and detailed crop management data. Details on crop growth simulation and model inputs are provided elsewhere (Grassini *et al.*, submitted; see Chapter 4). The purpose of these simulations was to compare WP, applied irrigation, and IWUE achieved by farmers with the values predicted by the simulation model with optimal irrigation. Hybrid-Maize simulates soil water dynamics as the balance between inputs from precipitation and/or irrigation and water losses through soil evaporation, crop transpiration, and percolation below the root zone. Under optimal irrigation mode, Hybrid-Maize estimates minimum water application requirement to achieve water stress-free growth. Crop water uptake is based on: (i) rooting depth and soil water potential, which in turn is based on water release characteristics as determined by soil texture; and (ii) maximum crop transpiration as estimated from reference evapotranspiration (ET_O) and leaf area index. An irrigation event is triggered whenever crop water uptake does not meet maximum transpiration. Although the amount of water applied per irrigation event can be altered in the Hybrid-Maize model to adjust for different types of irrigation systems (Yang *et al.*, 2006), in the present study we used the default value of 32 mm per irrigation event. Interception of incoming irrigation water by the crop at full canopy is set at 1.5 mm per irrigation event. Hybrid-Maize model was set to stop irrigation when soil water content of the top 30 cm reaches 95% of field capacity. Maximum root depth was set at 1.5 m based on soil water extraction patterns reported for irrigated maize (Payero *et al.,* 2006a).

Hybrid-Maize was also used to mimic effects of limited-irrigation management on yield and applied irrigation. The amount of water applied in each irrigation event under optimal irrigated mode was reduced by 25% throughout the crop cycle except for a -14 to +7d window around silking in which crops were kept fully irrigated. This approach was motivated by two observations: (1) the silking-pollen shed window is highly sensitive to water deficit (Otegui *et al.*, 1995), and (2) recent on-farm studies using this approach in eastern and central Nebraska reported substantial water savings with negligible impact on yield compared with fully-irrigated fields (Burgert *et al.*, 2009). Daily values of incident solar radiation, temperature, relative humidity, FAO-Penman-Monteith ET_O, and rainfall, as well as specification of soil properties (AWHC and soil texture) and soil water content at sowing are required to simulate soil water dynamics and irrigation requirements with Hybrid-Maize model. Relative humidity and ET_O for each field were interpolated from nearest meteorological stations as was done for incident radiation and temperature in Grassini *et al.* (submitted; see Chapter 4). Methodology to obtain daily values for rainfall, soil properties, and ASW_S in each of the 123 fields is described in Section 5.2.2. Estimated field-level water savings, calculated as the difference between actual and optimal- or limited-irrigation management, were scaled up to the 3-county Tri-Basin

NRD area to quantify the potential reduction in the annual water volume allocated to irrigated maize. Total irrigated maize land area in the Tri-Basin NRD was derived from USDA-NASS statistics (1999-2008) while the frequency and average size of the fields under different irrigation systems were retrieved from the Tri-Basin NRD database.

5.3. RESULTS

5.3.1. Benchmark for maize water productivity and evaluation versus observed data

The estimated mean WP function from the simulated data of Grassini *et al.* (2009b) had a slope of 19.3 ± 0.4 kg grain ha^{-1} mm^{-1} ($p < 0.001$, $r^2 = 0.75$) (Fig. 5-1a). Variation around the mean WP regression line results from normal variation in temperature, solar radiation, and water supply distribution among locations and years. The x-intercept, which is presumably an estimate of seasonal soil evaporation, was indistinguishable from the value derived from the boundary function (100 mm). Actual grain yield and water supply reported for rainfed and irrigated maize field experiments grown under near-optimal management practices in the Western U.S. Corn Belt were in reasonable agreement with the boundary- and mean WP benchmarks derived from simulated data (Fig. 5-1b). Irrigated crops grown in fields under subsurface drip irrigation, limited irrigation, and rainfed conditions with progressive management practices approached the boundary function. Most of the observations in Fig. 5-1b, however, were distributed around the mean WP function except for a few rainfed crop observations that were exposed to very severe water deficit during the critical silking-pollen shed window.

Coefficients of the linear regression between actual yields and water supply were not different from those of the mean WP function ($p > 0.70$; data not shown).

5.3.2. Total water supply and seasonal patterns of rainfall and maximum ET_C

Rainfall patterns during maize growing season in the Tri-Basin NRD varied greatly across years (Fig. 5-2a). Rainfall was below the 20-y average around silking in 2005, early in the growing season and around silking in 2006, and at end of grain filling in 2007. Simulated ET_C patterns were relatively stable across years except for some variation in the critical period around silking (Fig. 5-2b). Total seasonal water supply ranged from 898 to 971 mm across years (Fig. 5-2c). ASW_S (range: 210-290 mm) and sowing-to-maturity rainfall (range: 388-467 mm) accounted for ~25 and 45% of seasonal water supply, respectively. Higher ASW_S in 2007 was explained by above average rainfall during the non-growing season (data not shown). Average applied irrigation decreased from 342 in 2005 to 213 mm in 2007 due to higher rainfall and lower ET_C around and after silking in 2007. Separate regression analyses performed for each year indicated that variation in water supply was explained by applied irrigation (r^2 range: 0.86-0.96) but not ASW_S or sowing-to-maturity rainfall (r^2 range: 0.02-0.09) and this pattern was consistent across irrigation systems.

5.3.3. Actual and simulated water productivity in irrigated maize fields in central Nebraska

Yields from farmer's fields in the Tri-Basin NRD fell below the mean WP function although *ca.* 4% of the cases approached or even exceeded this benchmark (Fig. 5-3a, b). Average yield for these irrigated fields was 80% below the yield predicted from the mean WP function. In contrast, mean rainfed yield in the Tri-Basin counties (NASS-USDA, 2005-2007) was 53% of the yield predicted from mean WP benchmark for the same amounts of water supply. Grassini *et al.* (submitted; see Chapter 4) estimated a mean yield potential (Y_P) of 15.4 Mg ha^{-1} for the Tri-Basin NRD, which corresponds to a water supply value of 900 mm derived from mean WP function. This value represents the water supply required to achieve Y_P. Although grain yield rarely exceeded Y_P (only 13 out of the 777 field-years), 55% of total fields exceeded this water requirement threshold. Relatively fewer fields exceeded this 900 mm water supply threshold with pivot than with surface irrigation (45 versus 73% of fields).

The apparent water excess, calculated as the difference in seasonal water supply between observed values and the water supply for an equivalent yield from the mean WP function, was strongly related to applied irrigation ($p < 0.001$; r^2 range: 0.75-0.85) and weakly associated with ASW_S or sowing-to-maturity rainfall ($r^2 < 0.05$ across years) . Across all field-year observations, irrigated maize WP ranged from 8.2 to 19.4 with a mean of 14 kg ha^{-1} mm^{-1} (Fig. 5-4). Fields under pivot had 13% greater WP than counterparts under surface irrigation. WP was relatively stable across years as indicated by the small inter-annual coefficient of variation (4%). Interestingly, mean WP of irrigated fields was ~60% larger than estimated WP for rainfed maize fields. This difference may reflect the importance of water supply distribution during the growing season of rainfed crops and/or differences in agronomic management between irrigated and rainfed crops (*e.g.*, plant population, nutrient input levels, etc).

Grain yield with optimal irrigation was simulated for a subset of 123 fields using Hybrid-Maize model in combination with actual weather records and site-specific soil and management data (Fig. 5-3c). About 75% of simulated yields were within ±10% of predicted yields from the mean WP benchmark. Seasonal water supply values of simulated crops, calculated as the sum of actual ASW_S, sowing-to-maturity rainfall, and optimal irrigation water requirement as predicted by Hybrid Maize, were ≤ 900 mm in 88% of the simulated site-years. Whereas on average actual yields were 89% of simulated yields, Fig. 5-3c indicates that 25% of field-years, especially those with surface irrigation, had water supply values that exceeded simulated crop water requirements by >33%.

5.3.4. Impact of agronomic management on water productivity and irrigation efficiency

Statistical analyses of the detailed data on crop management collected from 123 of the 777 field-years indicated significant effects of irrigation system, previous crop, and tillage (all $p < 0.01$) on grain yield, applied irrigation amount, and/or IWUE(ΔY, I) (Fig. 5-5). While no difference in grain yield was observed between irrigation systems ($p > 0.20$), applied irrigation under pivot was 41% lower than under surface irrigation ($p < 0.001$). Within years, higher variation in applied irrigation amounts was observed with surface irrigation than under pivot (CVs = 44 *vs.* 31%). Also, applied irrigation under NT was 20% lower than under CT. Crop residues left in the field may reduce irrigation requirements by increasing precipitation storage efficiency during the non-growing season and by reducing direct soil evaporation and runoff as found by Nielsen *et al.* (2005) and Klocke *et al.* (2009). Hence, fields under pivot or NT exhibited higher IWUE(ΔY, I) than their counterparts with surface irrigation and CT. Impact of the tillage x previous crop interaction on grain yield was also notable: while no difference between tillage systems was observed when maize followed soybean, fields under continuous maize had higher yields with CT. Highest average IWUE(ΔY, I) (35 kg ha^{-1} mm^{-1}) *and* yield (13.5 Mg ha^{-1}) were obtained from fields under pivot irrigation, NT, and soybean-maize rotation.

There was no detectable effect of N fertilizer rate, sowing date, or seeding rate on irrigation amount ($p > 0.15$) across years or irrigation systems. Although short-season hybrids (RM 106-112 day) received 25 mm less irrigation water than full-season hybrids (RM 113-118 day), this difference was statistically significant only for fields under pivot in one year ($p = 0.03$).

5.3.5. Opportunities for increasing irrigation water efficiency through irrigation management

Large variation in IWUE(Y, I) was found as a result of differences in applied irrigation across years (Table 5-2). Mean IWUE(Y, I) was 35 and 61 kg ha^{-1} mm^{-1} for fields under surface irrigation and pivot systems, respectively (Table 5-2). Three-year pooled CVs were 20 and 28%, respectively for surface and pivot systems. When IWUE values were adjusted by subtracting average rainfed yield from irrigated yields in each year, resulting IWUE(ΔY, I) mean values were 19 (surface irrigation) and 32 kg ha^{-1} mm^{-1} (pivot), and year-to-year variation was reduced substantially (3-y pooled CVs = 11 and 14%). Average IWUE(ΔY, I) in the present study (26 kg ha^{-1} mm^{-1}) is similar to largest values of IWUE(ΔY, I) reported by Howell (2001) for maize grown under near-optimal conditions in Texas, U.S. (range: 17-25 kg ha^{-1} mm^{-1}) and well above Nebraska state-level IWUE(ΔY, I) average (16 kg ha^{-1} mm^{-1}) estimated from USDA-NASS data (FRIS, 2003-2008).

Grain yield, irrigation requirements, and IWUE(Y, I) also were simulated under two irrigation management scenarios (optimal and limited irrigation) using Hybrid-Maize model in combination with actual weather records and field-specific soil and crop management data for 123 maize field-year subset (Table 5-2). On average, mean actual applied irrigation under pivot and surface systems exceeded simulated optimal water requirements by 8% and 46%, respectively. Relative difference between simulated optimal and actual was greatest in the wettest year (2007). Elimination of applied irrigation excess and also the gap between actual and simulated Y_P would increase IWUE(Y, I) by 29 and 122% in pivot and surface systems, respectively. Finally, simulated IWUE(Y, I) under a limited-irrigation regime was 14% higher than with optimal irrigation due to a reduction in applied irrigation by 15% and only a 4% decrease in yield. Examination of the simulated water balances indicated that grain yield reduction was not proportional to the reduction in applied irrigation but rather to the decrease in ET_C with the limited-irrigation regime (data not shown). Simulated soil water dynamics revealed that greater water depletion from deep soil layers under limited irrigation, compared with optimal irrigation, ameliorated the impact of reducing irrigation water inputs on ET_C. These results are in agreement with (i) data reported by Stöckle and James (1989) for maize crops simulated under limited irrigation in soils with high AWHC and ASW_S similar to those in the Tri-Basin NRD, and (ii) on-farm studies of center-pivot maize fields in Nebraska where a limited-irrigation regime reduced applied irrigation by 45% without significant yield penalty compared with to farmer's irrigation management (Burgert, 2009).

Scaling-up of previous estimated field-level water savings to the entire 3-county Tri-Basin NRD area gave an estimated irrigation water-use reduction of 47 million m^3 y^{-1} from converting current maize fields under surface irrigation to pivot systems (Table 5-2). An additional reduction of 25 million m^3 would occur from more precise timing and amount of irrigation through greater congruence with actual crop water requirements (*i.e.*, optimal irrigation). Finally, additional water saving of 41 million m^3 was estimated if all farmers used pivot irrigation and utilized the limited-irrigation approach as simulated in this study although there would likely be a small yield penalty of about 4%.

5.4. DISCUSSION

Useful benchmarks are those based on understanding of biophysical processes that determine crop productivity in response to environment x management interactions. The challenge is translating these complex processes into practical decision-support tools of use to farmers and policy-makers. The WP benchmark established in the present study offer a robust and relatively straightforward framework to quantify and improve WP of irrigated maize systems, and this framework could be used on other irrigated crops as well. Evaluating yield for a specific field relative to the attainable yield with the same water supply on the mean WP benchmark regression estimates the yield gap. In the Tri-Basin NRD, for example, the average size of this grain yield gap was 2.3 Mg ha^{-1}. The larger the magnitude of this gap, the lower the WP. Likewise, difference in water supply on the mean WP benchmark regression line at current yield levels and water supply for a given field (or district) indicates the potential water excess above crop water requirements for the same yield level. On average, the apparent water excess for irrigated maize in the Tri-Basin NRD was 170 mm (median: 145 mm). Thus, benchmark comparisons can be made to quantify WP of individual fields or for entire irrigation districts, regions, and states. Depending on the particular objective, farmers can improved WP by (i) reducing the yield gap at the same level of water supply (*e.g.*, better crop, nutrient, and pests management), (ii) maintaining yield with a reduced level of water supply (*e.g.*, better irrigation management), or (iii) combining the previous two approaches.

Analysis of farm yields and water supply of a large number of individual fields over several years helps identify maximum attainable yield levels with current management practices in a given region. In the Tri-Basin NRD, maximum field yields rarely exceeded the mean yield potential estimated by simulation (15.4 Mg ha^{-1}), which required a total water supply of about 900 mm based on the WP regression line. Fields that received more than this amount were over-watered. Likewise, to increase relevance of the mean WP function as a benchmark, it is useful to consider any Tri-Basin NRD water supply value > 900 mm as equal to 900 mm for calculation of yield gaps or the potential water savings.

Such an approach was used in the above calculations for mean yield gap and water saving potential in the Tri-Basin NRD.

The present study shows that on-farm data can be used to identify specific technologies and crop management options that increase irrigation water-use efficiency and to quantify the potential impact of these technologies on irrigation water use and crop production at field to regional levels. Resulting information can be then used to support policies and incentives that help farmers adopt practices that reduce water and energy used for irrigation. For example, available field-scale options in the Tri-Basin NRD to reduce applied irrigation amounts without yield loss include converting current surface irrigation systems to pivot, fine-tuning of irrigation scheduling, and implementation of conservation tillage in fields under soybean-maize rotation. Total annual water saving from adoption of the first two of these practices (*i.e.*, converting existing surface systems to pivot, fine-tuning of current irrigation schedule) represents ~ 32% of the total annual water volume allocated to irrigated maize in the Tri-Basin NRD.

Increasing scarcity and greater competition for use of freshwater resources will force irrigated agriculture to be more efficient in use of available supplies. Quantification of water use and WP in actual irrigated cropping systems provides critical information to guide policies and regulations about water use and allocation with the goal of maintaining or increasing productivity while protecting natural resources. A concern is whether the WP benchmark developed in this study can be used to perform assessments of maize WP, identify constraints, and predict impact of management options in other regions with different climate. While the biophysical link between crop production and water supply will hold across environments, the three parameters that define the WP benchmark (*x*-

intercept, slope, and Y_P) may change as a result of climatic and/or management differences. Hence, with appropriate calibration of these parameters, the maize WP benchmark approach can be used beyond the Western U.S. Corn Belt. For example, the value of the slope of the WP function can be related to site-specific seasonal daytime vapor pressure deficit or ET_O (Sadras and Angus, 2006). Preliminary results for a major maize-producing region in China (Yellow-Huai River Valley) indicate that slope of the mean WP function for maize is 25% greater than the slope derived for Western U.S. Corn Belt due to a more humid climate. Likewise, average maize Y_P in Yellow-Huai River Valley is 33% lower than average Y_P in Tri-Basin NRD as estimated by Bai *et al.* (2010) using a crop simulation model in combination with long-term weather data and actual management practices.

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Table 5-1. Sources of grain yield and water supply data used to validate the water productivity benchmark shown in Fig. 5-1. All of these field studies were located in the Western U.S. Corn Belt and used optimal management practices.

Source	Locations [†]	Years	Water regime	Irrigation system	Field description
Burgert (2009)	Edgar, Geneva, Hordville, Mead, Wahoo, West Point, York	2007-2008	Irrigated (n = 30) [‡]	Center-pivot	Farmers' fields (50-60 ha)
Hergert *et al.* (1993)	North Platte	1983-1991	Irrigated (n = 16) and rainfed (n = 9)	Solid-set sprinkler	Experimental plots (0.06 ha)
Irmak and Yang, unpublished data	Clay Center, North Platte	2005-2006	Irrigated (n = 14) and rainfed (n = 4)	Subsurface drip irrigation	Experimental plots (0.1 ha)
Payero *et al.* (2006a)	North Platte	1992-1996	Rainfed (n = 5)	--	Experimental plots (0.1 ha)
Payero *et al.* (2006b)	North Platte	2003-2004	Irrigated (n = 15) and rainfed (n = 2)	Solid-set sprinkler	Experimental plots (0.02 ha)
Payero *et al.* (2008)	North Platte	2005-2006	Irrigated (n = 16)	Subsurface drip irrigation	Experimental plots (0.1 ha)
Suyker and Verma (2009)	Mead	2001-2006	Irrigated (n = 8) and rainfed (n = 3)	Center-pivot	Experimental plots under progressive management (50-65 ha)
Yang *et al.* (2004)	Manchester	2002	Rainfed (n = 1)	--	Farmer field, winner of National Corn Growers yield contest (≈ 30 ha)

[†] All sites are located within Nebraska, except for Manchester (Iowa).
[‡] For each site-year, separate fields were either irrigated by the farmer's standard irrigation practices or by a limited-irrigation approach.

Table 5-2. Grain yield (GY; Mg ha^{-1}), irrigation (I; mm), and irrigation water use efficiency (IWUE; kg ha^{-1} mm^{-1}) for a subset of 123 field-years in the Tri-Basin Natural Resources District (NRD) under actual irrigation management (disaggregated by irrigation system) and simulated optimal - or limited-irrigation.

Year	Actual irrigation†						Simulated optimal irrigation‡			Simulated limited-irrigation‡		
	Surface			Pivot								
	GY	I	IWUE¶	GY	I	IWUE	GY	I	IWUE	GY	I	IWUE
2005 (*n* = 33)	13.7	493	28 [18]	13.6	313	44 [27]	15.3	265	58	14.4	225	64
2006 (*n* = 33)	12.9	359	36 [21]	12.8	208	62 [37]	15.1	241	63	14.8	207	72
2007 (*n* = 57)	13.1	313	42 [18]	12.9	166	77 [32]	14.2	124	114	13.9	106	131
Mean	13.3	388	35 [19]	13.1	229	61 [32]	14.8	210	78	14.3	179	89
Tri-Basin total§	582	114		1167	238		1975	279		1909	238	

† Data based on actual yield and applied irrigation.

‡ Grain yield and optimal irrigation amounts were simulated using Hybrid-Maize model in combination with actual weather records and field-specific soil and crop management data; assumes all fields were irrigated by center pivot.

¶ IWUE calculated as the ratio of grain yield to applied irrigation [IWUE(Y, I)] or irrigated yield minus 3-county average rainfed yield to applied irrigation [IWUE(ΔY, I), shown between brackets]. IWUE(ΔY, I) was not calculated under simulated optimal- or limited irrigation due to lack of model inputs for simulating rainfed yields.

§ Assuming 78 and 22% of the irrigated maize cropland area in the Tri-Basin NRD (133,000 ha) to be under pivot and surface categories, respectively, based on frequency and average size of the fields under surface and pivot included in the database analyzed in this study. Total production and irrigation volume are expressed in Mg x 10^3 and m^3 x 10^6, respectively.

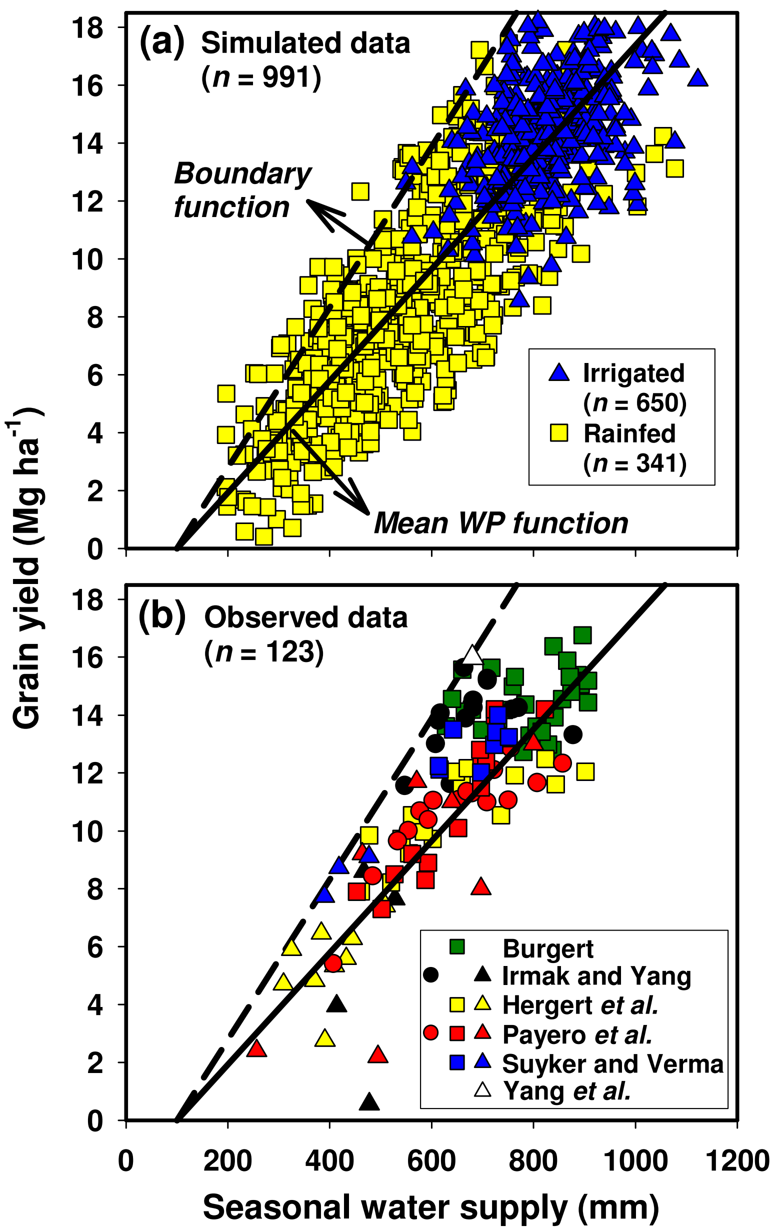

Figure 5-1. (a) Relationship between simulated maize grain yield and seasonal water supply (available soil water at sowing to 1.5 m depth, plus sowing-to-maturity rainfall and applied irrigation), modified from Grassini *et al.* (2009b). Dashed and solid lines are the boundary- and mean water productivity (WP) functions, respectively (slopes = 27.7 ± 1.8 and 19.3 ± 0.4 kg ha^{-1} mm^{-1}, respectively; *x*-intercept = 100 mm). Outlier observations are not shown. (b) Actual grain yield and water supply data from field studies in Western U.S. Corn Belt managed to produce yields without limitation from nutrients or pests under rainfed (▲), irrigated-sprinkler or pivot [■] or subsurface drip irrigation [●]). Data source description and citations are provided in Table 5-1.

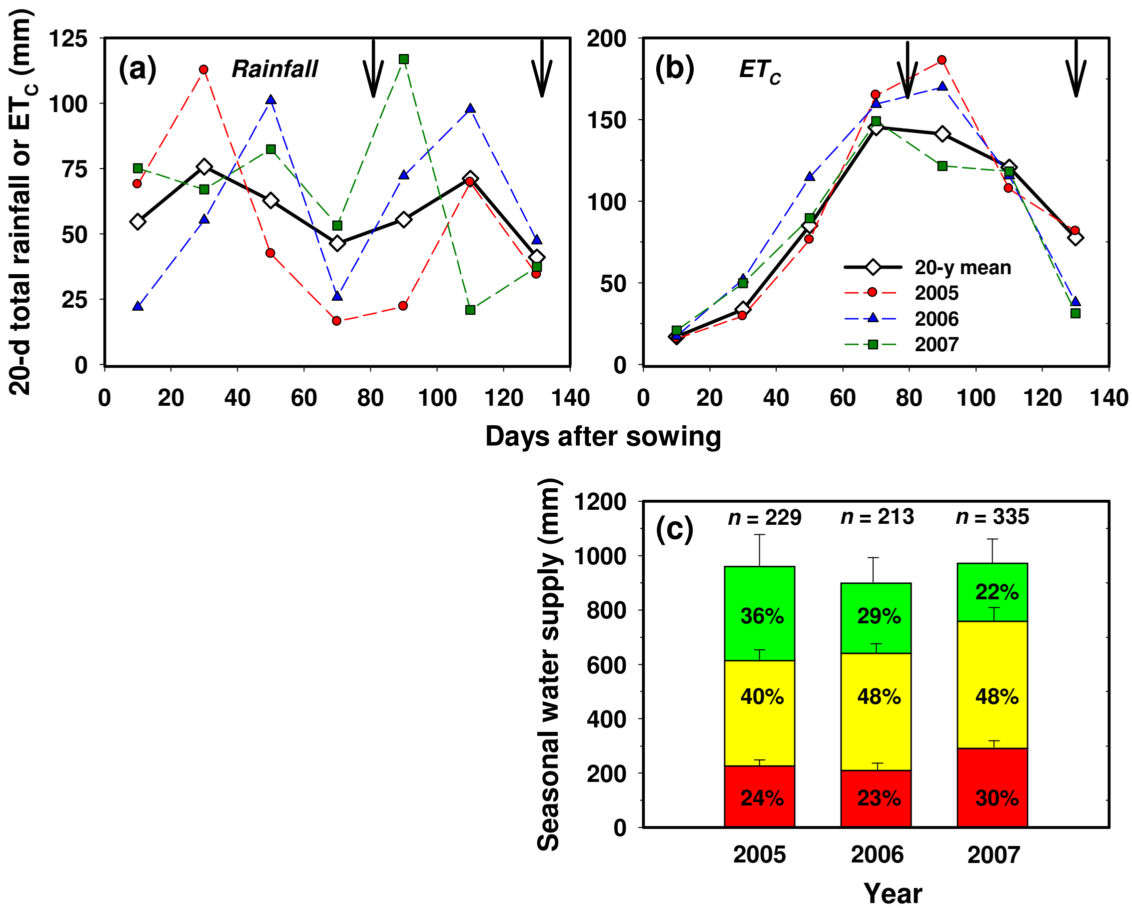

Figure 5-2. (a-b) Patterns of 20-day total rainfall and simulated crop evapotranspiration under non-limiting water supply (ET_C) using the Hybrid-Maize model for maize crops with average management practices (sowing date: DOY 114, 115, and 123, respectively; relative maturity: 113 d; 7.2 plants m^{-2}) used in the Tri-Basin NRD in 2005-2007 seasons. Each observation is the average of four locations inside or near the Tri-Basin Natural Resources District (NRD). Vertical arrows indicate dates of silking and physiological maturity (left and right arrow, respectively). (c) Total water supply during maize growing seasons, disaggregated by available soil water at sowing, sowing-to-maturity rainfall, and applied irrigation (bottom, mid, and top bars, respectively), shown as mean values from irrigated maize fields in the Tri-Basin NRD. Values inside bars are percentage of total water supply in each year. Error bars indicate the standard deviation of each water supply component.

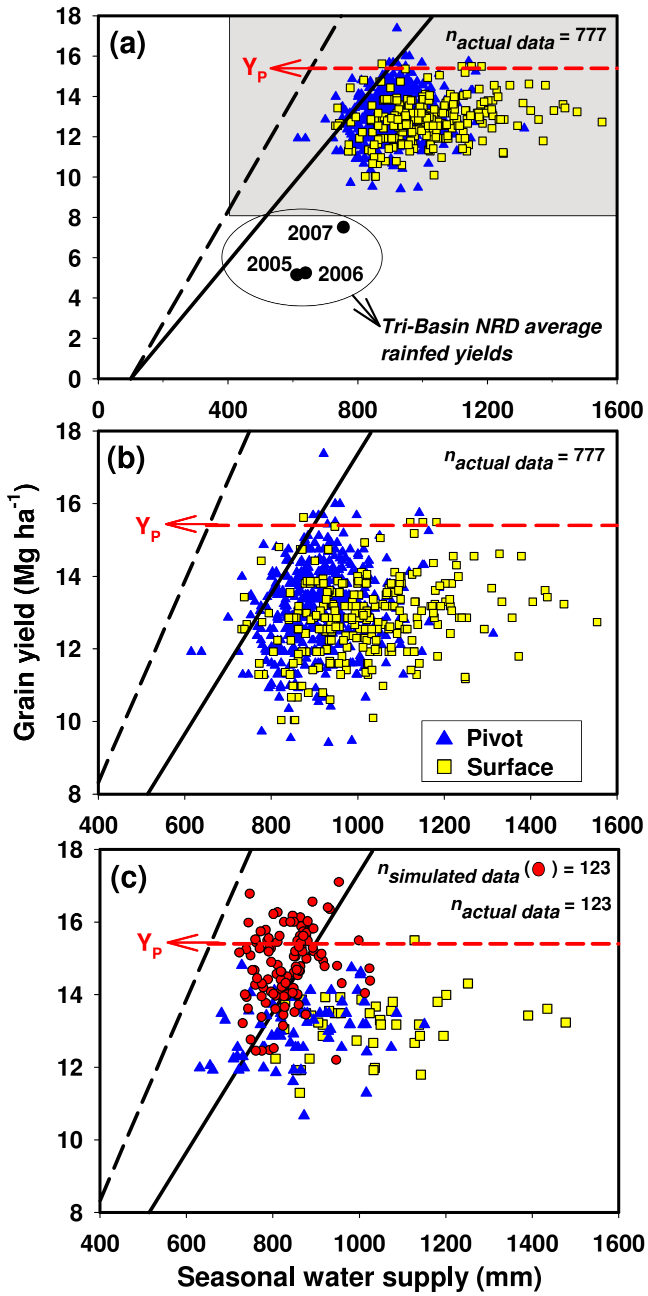

Figure 5-3. (a) Relationship between farm grain yields and seasonal water supply (available soil water at sowing plus sowing-to-maturity rainfall and applied irrigation) from 777 field-years in the Tri-Basin Natural Resources District. Average rainfed yields for the three Tri-Basin counties were obtained from NASS (2005-2007) and are shown for comparison. Data within shaded area are shown (b) disaggregated by irrigation system type, or (c) as actual yield versus simulated yield (●) with optimal irrigation based on output from the Hybrid-Maize model in combination with actual weather records and crop management data collected from a subset of 123 fields. The dashed and solid lines are the boundary- and mean water productivity functions, respectively, as shown in Fig. 5-1. Note scale differences for axes in (a) versus (b) and (c).

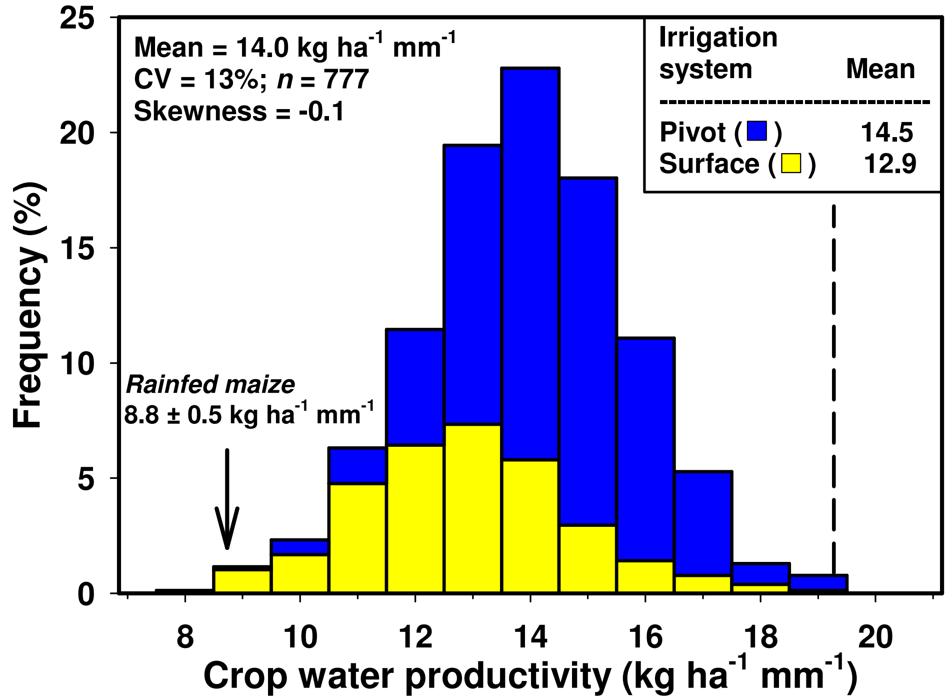

Figure 5-4. Frequency distribution of crop water productivity (WP) for irrigated maize fields in the Tri-Basin Natural Resources District. WP was calculated as the ratio of grain yield-to-seasonal water supply; frequencies are disaggregated by irrigation system. Statistical distribution parameters are shown in upper left. Vertical dashed line indicates the attainable WP derived from the slope of the mean WP function as shown in Figure 1. Vertical arrow indicates mean WP for rainfed crops.

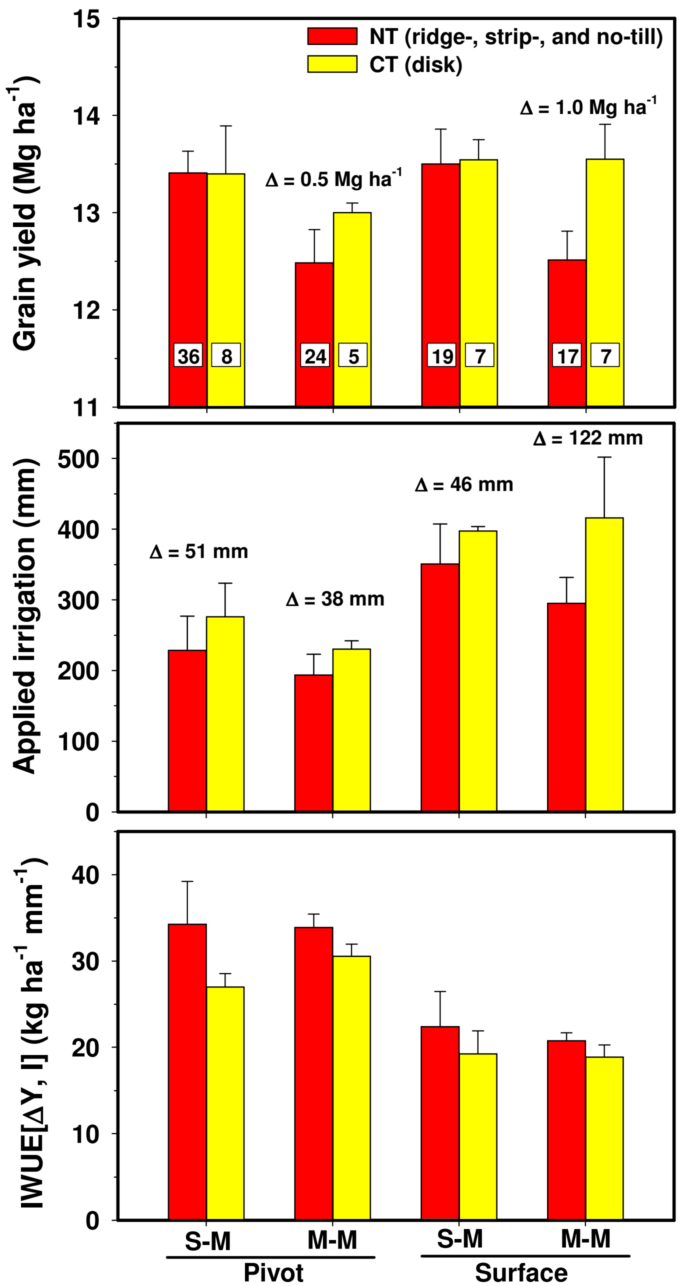

Figure 5-5. Mean (±SE) grain yield, applied irrigation, and irrigation water use efficiency [IWUE(ΔY, I)] under different combinations of irrigation system (pivot or surface), rotation (soybean-maize [S-M]; maize-maize [M-M]), and tillage (no-till [NT]; conventional [CT]) in irrigated maize fields in the Tri-Basin Natural Resources District. All values are 3-yr means (2005-2007). IWUE(ΔY, I) was calculated as the ratio of (irrigated yield minus average rainfed yield) to applied irrigation. Values inside bars in the top panel indicate number of observations for each irrigation system x rotation x tillage combination. Differences (Δ) for selected comparisons between tillage systems are shown.

CHAPTER 6: RESEARCH IMPACT AND RESULTING QUESTIONS

Summary

Major findings of this Ph.D. dissertation are summarized, highlighting tangible outcomes and resulting questions. Potential uses of biophysical benchmarks and on-farm data are illustrated. Four cropping systems, with contrasting environmental and technological features, are compared to evaluate how resource-use efficiency (focussing on water and nitrogen [N]) varies across yield and resource-input levels. Future maize production scenarios are explored in view of national-level yield trends in major producing countries, management and breeding opportunities to increase yield potential (Y_P), and climate change impacts. The present study defined the most sensitive factors for maize production in the Western U.S. Corn Belt including Y_P, water-limited yield potential (Y_{P-W}), yield-gap size, and resource-use efficiency. Complementary use of farmer's data and biophysical benchmarks proved to be a powerful tool to diagnose and identify ways for increasing yield and resource-use efficiency in cropping systems. Irrigated maize systems in the Western Corn Belt are operating near Y_P and exhibit higher water productivity (WP) than other intensive and low-input cropping systems. Although N fertilizer-use efficiency (NUE) has increased steadily since 1980, there is still room for improvement as N-fertilizer recovery efficiency (RE) is only 43% of applied N-fertilizer. Evidence of yield plateaus, as observed in the Tri-Basin Natural Resources District, appear to be a widespread phenomenon in other irrigated maize systems as inferred from national-level yield trends. Substantial increase in Y_P is required

to meet future maize demand and avoid environmental consequences that would result from land-use changes. Opportunities for increasing Y_P include further tuning of management practices and selection for grain yield in trials managed under near-potential conditions. Negative impacts of climate change trajectories on maize yields are likely to be counterbalanced by continuous farming adaptation and breeding for stress tolerance.

Keywords: yield potential, yield gap, resource-use efficiency, benchmark, on-farm data

Abbreviations: Y_P: yield potential; $Y_{P\text{-}W}$: water-limited yield potential; IWUE: irrigation water use efficiency (kg grain mm^{-1} applied irrigation); N: nitrogen; NRD: Natural Resources District; NUE: nitrogen fertilizer-use efficiency (kg grain kg^{-1} N fertilizer); P: phosphorous; RE: N fertilizer recovery efficiency (kg N uptake kg^{-1} N fertilizer); WP: water productivity (kg grain mm^{-1} water supply).

6.1. Key research findings

The present research defined key parameters concerning the performance of maize systems in the Western U.S. Corn Belt. Simulation modeling, based on actual weather data, soil properties, and accurate specifications of management practices, provided an effective way to estimate yield potential (Y_P) and water-limited yield potential ($Y_{P\text{-}W}$) (Chapter 2). A biophysical benchmark for water productivity (WP; defined here as the amount of grain per unit of water supply) was developed and used, in combination with on-farm data, to evaluate current yield levels and resource-use efficiencies (focusing on water and nitrogen inputs [N]) in a high-yield irrigated maize system (Chapters 4 and 5). Two major findings of this research were: (i) both yield level and resource-use efficiency can be high in well-managed intensive cropping systems and (ii) irrigated maize fields in the Western U.S. Corn Belt are operating, on average, close to the Y_P ceiling, which highlights the need for substantial increase in maize Y_P to allow future increases in farmer's yields.

Tangible outcomes from the research include an estimate of average Y_P for irrigated maize in the Western U.S. Corn Belt and development of a WP benchmark which allows estimation of $Y_{P\text{-}W}$, yield gaps, and water excess (Chapters 2, 4, and 5), derivation of algorithms for the estimation of initial soil water content at sowing (Chapter 3), and guidelines for increasing irrigation water- and fertilizer N-use efficiencies (NUE) by further tuning of current management practices (Chapters 4 and 5). These outcomes can be adopted by farmers and crop consultants aiming to increase yields and resource-use efficiency as well as researchers and policy-makers aiming to diagnose and increase regional and global efficiency of existing cropping systems.

Conclusions arising from the studies reported in this dissertation are summarized below:

- Simulated average Y_P and $Y_{P\text{-}W}$ in the Western U.S. Corn Belt were 14.4 and 8.3 Mg ha^{-1}, respectively, based on current management practices and actual weather and soil properties. Geospatial variation of Y_P was associated with solar radiation and temperature during the post-anthesis phase while variation in $Y_{P\text{-}W}$ was linked to longitudinal variation in seasonal rainfall and evaporative demand;

- On average, actual farmer's yields of irrigated maize were 89% of Y_P, and average WP and NUE were high despite application of large amounts of irrigation water and N fertilizer;
- A linear relationship between Y_{P-W} and water supply (slope: 19.3 kg ha^{-1} mm^{-1}; x-intercept: 100 mm) can be used as a benchmark to diagnose and improve farmer's WP and irrigation management;
- While there is limited scope for substantial increases in actual average yields, WP and NUE can be further increased by: (1) switching surface to pivot systems, (2) using conservation instead of conventional tillage systems in soybean-maize rotations, (3) implementation of irrigation schedules based on crop water requirements, and (4) better N fertilizer management;
- Analysis of soil water recharge indicates that 80% of variation in soil water content at sowing can be explained by precipitation during the non-growing season and residual soil water at end of previous growing season.

6.2. Diagnosing cropping system performance with biophysical benchmarks

Useful benchmarks for crop production are those based on the understanding of biophysical processes that link yields to environmental factors. The challenge is to translate these benchmark relationships into practical decision-support tools for farmers and policy-makers. The mean WP function developed in the present research in an example of a biophysical benchmark that can be used to diagnose and improve on-farm resource-use efficiency (Chapter 5). Three major aspects make the mean WP function an attractive tool for benchmarking cropping system performance because: (i) variables (grain yield and water supply) that define WP are meaningful and easily estimated for use by farmers, crop consultants, and policy-makers, and (ii) the gap between actual yield and the benchmark can be used to help identify limiting factors and improved management to increase yields and WP.

The WP benchmark can be adopted by Natural Resources Districts and growers associations in Nebraska to evaluate district-level WP and use this information to justify incentives that promote adoption of new management strategies that lead to higher yield with reduced irrigation. Likewise, the WP benchmark can be used as a decision-support tool to implement water allocation policies to increase district-level yield and WP (Fig. 6-1a). Considering three farms (A, B, and C) with contrasting yield and water supply in an initial scenario (1): Y_P limited by water supply, high WP (A1); Y_P limited by water supply, low WP (B1); and Y_P not limited by water supply, low WP (C1). In the new scenario (2), the three farms equally increase the amount of applied irrigation water such that none of the farms are limited by water supply. However, whereas one farm achieves Y_P and maximum WP (A2), productivity in the other two farms (B2 and C2) is still constrained by yield-limiting factors other than water. Moreover, one farm (C2) has a water supply on excess to crop water requirements required to achieve Y_P. Irrigation water allocation can be optimized based on the relative position of each farm to the WP benchmark. For example, farm A qualifies to receive more water, farm B may qualify after identification and elimination of factors that cause low WP, and farm C does not qualify as its water supply is not limiting for achieving Y_P. Likewise, the WP benchmark is applicable to a limiting-water supply scenario in which an irrigation district is required to reduce applied irrigation amounts: farms with water supplies on excess to crop water requirement for achieving Y_P and/or low WP (B2 and C3) are likely candidates for water allocation restrictions.

A concern is whether the WP benchmark developed in the present study can be extrapolated to other cropping systems to perform assessments of production level and WP. While the biophysical link between crop production and water supply holds across environments and species, the parameters that define the WP benchmark (*x*-intercept, slope, and Y_P) may change as a result of climatic, genetic, and/or management differences. Hence, with the appropriate calibration, the maize WP framework can be used beyond the Western U.S. Corn Belt. This case is illustrated for a major maize-producing region in China (Fig. 6-1b) where average maize Y_P was estimated using a simulation model in combination with long-term weather data and actual management practices (Bai *et al.*, 2009) and the slope of the mean WP function was assumed to be (inversely) related to mean daytime vapor pressure deficit or reference evapotranspiration over the crop growing season (Tanner and Sinclair, 1983; Sadras and Angus, 2007). While a formal validation of the WP benchmark calibrated for Yellow-Huai River Valley in China was not attempted due to lack of data on actual farm management and yield levels, the example illustrates potential applicability of the WP benchmark in other cropping systems by adjustment of its parameters according to location-specific evaporative demand and Y_P.

6.3. Farmer’s data as basis for performing cropping system-analysis

Results from the present research highlight the potential use of high-quality on-farm data, in combination with simulation modeling and geospatial tools, for performing cropping-system analysis (Chapters 4 and 5). On-farm data analysis has several limitations as there is a lack of experimental design and replication that limits the ability to identify cause-effect relationships using traditional ANOVA techniques. This analysis served, however, as a proxy to identify key technological and environmental factors that affect productivity and resource-use efficiency in commercial farms. Perhaps more important, when complemented with biophysical benchmarks or simulation modeling, on-farm data allow quantification of yield-gap size in and identification of major yield-reducing factors and corrective measures. Likewise, results derived from on-farm data analysis can serve as basis for justifying further research on specific topics. For example, the present study identified interactions between rotation and tillage system on grain yield (Chapter 4). Whereas rotation and tillage effects on rainfed yields have multiple causes, including residual N and water from the previous crop and disease pressure (Kirkegaard *et al.*, 2008), there is no explanation for such effects on yield of crops that received adequate supplies of nutrients and water and when other yield-reducing factors are effectively controlled (Verma *et al.*, 2005). Likewise, the present research indicates a consistent reduction of irrigation water requirements in fields under conservation tillage compared with their counterparts under conventional tillage (Chapter 5). Increasing adoption of conservation tillage by U.S. farmers and irrigation water-use restrictions justify funding on research directed to identify explanatory causes for observed tillage and rotation effects on yield and irrigation water requirements.

On-farm experimentation is necessary, on the other hand, to validate tools and management options derived from experimental plots and simulation modeling. For example, algorithms for estimation of initial soil water content at sowing reported in this study (Chapter 3) can be easily validated against soil water measurements taken at the beginning of summer-crop growing season in farmer's fields. Likewise, limited-irrigation tactics based on understanding of crop water requirements at critical developmental stages for yield determination (Chapter 5) can be tested in selected farmer's fields and serve as basis for extension education and development of real-time irrigation decision-support tools. A first step in this direction is validation of limited-irrigation schemes performed by Burgert *et al.* (2009) in farmer's fields in eastern Nebraska that allows a 45% reduction in applied irrigation amounts without yield penalty.

6.4. Integrating field observations and biophysical benchmarks to evaluate and compare cropping-system performance

Four cases of cropping systems with contrasting environmental and technological features are presented: irrigated maize in the Western U.S. Corn Belt (Chapters 4 and 5, present study), irrigated dry-season rice in the Philippines (Cassman *et al.*, 1996; Taball *et al.*, 2002), rainfed sunflower in semiarid central Argentina (Grassini *et al.*, 2009), and rainfed wheat in south-eastern Australia (Sadras *et al.*, 2002, 2004). The objectives are (i) to illustrate how biophysical benchmarks and farmers' databases can be combined to diagnose cropping-system performance in terms of yields and resource-use efficiencies, and, (ii) to compare resource-use efficiency (focusing on water and N) among cropping-systems with different yield levels and resource inputs.

Attainable and actual yields increased from low-input rainfed crop systems (wheat and sunflower) to intensive irrigated systems (rice and maize) with a parallel reduction in size of the gap between actual and attainable yields (Table 6-1, Fig. 6-2). Irrigated maize in U.S. Corn Belt exhibited the highest WP compared with other intensive (rice) and low-input systems (wheat and sunflower). Despite the actual average rice yield in the Philippines was about 70% of Y_P, WP was very low as a result of large water inputs. Likewise, rainfed wheat and sunflower yields were well below the WP benchmarks even in years in which the water supply was not limiting (Fig. 6-2). Explanatory factors for large gaps between actual and attainable yields in rainfed cropping systems included suboptimal N and P fertilizer inputs, lack of adoption of conservation tillage and crop rotations, inadequate control of biotic factors, and soil chemical constrains to root growth (Table 6-1).

The largest N fertilizer inputs corresponded to irrigated maize and rice while N supply in rainfed sunflower and wheat systems was highly dependant upon indigenous soil N supply as N fertilizer accounted for less than 15% of estimated crop N uptake. Continuous cropping with minimum N fertilizer inputs, as shown in the rainfed systems in Table 6-2, leads to a progressive mining of soil indigenous N which represents a symptom of resource degradation rather than high efficiency. N fertilizer-use efficiency (NUE) and recovery efficiency (RE) in U.S. irrigated maize were 16 and 31% higher than for rice in Philippines and in the lower range of NUE and RE values reported by Doberman *et al.* (2005) for well-managed systems.

A corollary of the above analysis is that well-managed intensive systems can achieve high resource-use efficiencies without compromising cropping-system sustainability. This conclusion contrasts with the common belief that resource-use efficiency in intensive cropping is intrinsically low as a result of “leakiness” of applied inputs and related environmental consequences as observed during 1980’s in U.S. Corn Belt (Keating *et al.*, 2010). Steady increase in actual yields and better management of N fertilizer and irrigation water appear to be major drivers of current high resource-use efficiency in intensive maize systems in U.S. Corn Belt (Fig. 6-3). While N fertilizer rates remained flat during last 20 years (average: 155 kg N ha^{-1}), irrigation amount decreased from 364 mm (1970-1980 period) to 282 mm (1990-2000 period) although the trend may be biased by differences in rainfall between the two periods (as inferred from rainfed yields in Fig. 6-3, bottom panel). Remarkably, NUE and irrigation water-use efficiency (IWUE; calculated as ratio of irrigated minus rainfed yield to applied irrigation) increased by 39 and 46% during the same interval. Much of the change in NUE and IWUE was due to hybrids more tolerant to higher plant population and insect pests and diseases, a shift from gravity to sprinkler irrigation in many areas, and better N fertilizer and irrigation-water management.

Low resource-use efficiency is, however, still common in some intensive cropping systems. For example, Cui *et al.* (2008) reported average winter-wheat NUE and RE of 20 kg grain kg N^{-1} and 0.18 kg N kg^{-1} N, respectively, in farmer’s fields in the North China Plains where average yield and N fertilizer rate were 5.8 Mg ha^{-1} and 325 kg N ha^{-1}. Likewise, WP in irrigated systems in eastern Asia appears to be very low as shown previously for rice in the Philippines (Table 6-1). Hence, tremendous scope exists for increasing resource-use efficiency in these intensive cropping systems through targeted changes in current management practices (*e.g.*, Belder *et al.*, 2004; Cui *et al.*, 2008).

Low nutrient inputs in rainfed systems (Table 6-1) reflect adjustment to lower attainable water-limited yield and, perhaps more crucial, farmer's risk-aversion attitude derived from the erratic response to fertilization due to incidence of drought and other yield-reducing factors (*e.g.*, diseases, lodging, and co-limitation with other nutrients). Identification of yield-reducing factors and correction through adoption of specific management practices may result in higher productivity and resource-use efficiency. For example, adoption of conservation tillage, inclusion of canola in rotations, and use of cultivars resistant to root diseases in the Australian wheat belt lead to higher and more stable wheat yields which, in turn, encouraged farmers to apply higher N fertilizer rates (Angus, 2001; Connor 2004; Passioura, 2007). As a result, more farms in southeastern Australia are now limited by water supply, *i.e.*, reaching the WP benchmark for wheat shown in Fig. 6-2.

6.5. Yield potential: implications for food security, opportunities for improvement, and climate change impact

Estimation of Y_P (and Y_{P-W} when water is limiting) in major cropping systems of the world is needed for assessing future scenarios of food security (Chapter 1), and research reported in this dissertation is a first step toward that direction. The next step would be to estimate country-level Y_P that can be compared against national yield trends to quantify yield gaps. There is, however, an increasing difficulty for estimating yield gaps based on individual fields to regional or national levels due to extreme sensitivity of Y_P to geospatial variations in weather, soil, and management practices. For example, the yield gap in Tri-Basin NRD (Chapter 4) varied from 11% of Y_P, when its estimation was based on field-specific data for a limited a number of years, to 21 or 30% of Y_P when using long-term weather in combination with average or optimal management practices, respectively. Hence, robust estimation of country-level Y_P and yield gaps requires explicit and accurate specification and interpolation of weather, soil, and crop management variables as well as adequate weighting of Y_P estimated for different cropping systems within the same country. First steps in this direction performed for rice in China and maize in the USA highlight the difficulty of this task (van Wart, J, *unpublished results*).

Farmers in the irrigated maize systems in the U.S. Corn Belt are operating close to Y_P as previously observed for other crops in intensive cropping systems (Chapter 1). Average irrigated maize yields in the Western U.S. Corn Belt will remain around current yield levels without substantial increases in Y_P, although exceptional higher or lower yields can be expected as a result of typical year-to-year variations in weather. Symptoms of yield plateaus, as shown in the present study (Chapter 4), emerge from national-level yield trends in major maize-producing countries (Fig. 6-4, Table 6-2). While linear increases in actual yield are observed for rainfed cropping systems (*e.g.*, USA, Brazil, Mexico), there is evidence of yield plateaus in intensive irrigated cropping systems (*e.g.*, USA, China, southern Europe) although longer time series are needed to confirm these trends in some cases. In agreement with the findings of the present study (Chapter 4), symptoms of yield plateaus in irrigated maize in the USA and China occur when farmer's yields reached 70-80% of country-level Y_P (van Wart, J., *unpublished results*). Without substantial increases in the current Y_P, growing demand for maize for food, livestock feed, and biofuel would require: (i) increasing productivity in current rainfed systems through elimination of yield gaps or access to supplemental irrigation water and/or (ii) increasing maize cropland area at the expense of other crops and natural ecosystems. Increments in rainfed production may be constrained by available cost-effective technology and limited access to irrigation water while land-use changes might involve destruction of biodiversity-rich ecosystems and related ecosystem services (Chapter 1). Therefore, sustainable increase in maize production over the next 50 years requires increasing productivity in existing intensive cropping systems which, ultimately, requires a substantial increase of current Y_P level. A crucial point is, therefore, to know which avenues are available for increasing maize Y_P.

As long as maize demand and prices remain high, farmers may increase Y_P slightly (10-15%) through further adjustment of crop management practices such as earlier sowing date, higher plant population densities, and longer maturity (Chapters 1 and 4). From a physiological viewpoint, Lee and Tollenaar (2002) and Denison (2009) concluded that most avenues for increasing Y_P *per se* through genetic improvement have been exhausted although some opportunities still remain such as functional stay-green during grain filling, optimization of sink establishment dynamics during kernel set, and manipulation of interplant competition. So far, early selection of inbred lines based on grain yield measured in high plant-population trials, managed under potential-growth conditions, represents the most cost-effective way for increasing Y_P (Duvick and Cassman, 1999; Lee and Tollenaar, 2002). Selection for Y_P will requires a parallel effort to make crops less susceptible to barrenness, lodging, green snap, diseases, weeds, and insect pests (Denison, 2009).

The previous discussion on traits that lead to higher Y_P also applies to Y_{P-W} as traits that increase Y_P usually increase water-limited yield as well (Specht *et al.*, 2001; Araus *et al.*, 2003). However, this response may not operate in the opposite direction as constitutive traits that increase drought tolerance in harsh environments may have yield penalties when water is not limiting (*i.e.*, lower Y_P). It is crucial, therefore, to evaluate potential trade-offs between attainable water-limited and Y_P before implementing breeding program focusing on specific drought-tolerance traits (Specht *et al.*, 2001; Blum, 2005; Denison, 2009). Examples of viable opportunities that may increase maize attainable water-limited yield without penalties on Y_P include anthesis-silking synchrony and floret survival under water stress (Saini and Westgate, 2002; Ribaut *et al.*, 2004), osmotic adjustment (Chimenti *et al.*, 2006), changes in root architecture (Hammer *et al.*, 2009), and tolerance to soil chemical toxicities (Sierra *et al.*, 2006). So far, the most effective way to increase yield in rainfed maize systems is to increase water supply and/or fraction of water supply transpired by the crop, for example, through better fallow management, conservation tillage, healthier root systems, and access to supplemental irrigation where feasible (Loomis and Connor, 1992; Passioura, 2006).

Although there is controversy on the driving forces and magnitude of current climate change (Idso and Singer, 2009), there is general consensus that temperature is increasing steadily (IPCC, 2007). Rates of crop physiological processes depend on temperature; therefore, global warming may change Y_P and actual yields although direction and magnitude of this change is uncertain. Lobell (2007) summarizes projections of temperature increase during maize growing season in 2050 and the impact on cereal grain yields in major producing countries (Table 6-3). Average projected increase in mean temperature predicted by 11 climate models ranged from 1.9 (Argentina) to 3.0°C (USA). In the same study, effects of predicted average rise in temperature on yield were estimated from empirical relationships between historical weather data and national crop yields. Results ranged from very little change (China) to a large decrease in maize yield (USA) although for all countries but one the confidence interval includes the chance of no-yield change.

The Lobell *et al.* (2007) study and other published estimates of climate change impacts on crop yields do not account for changes in rainfall, solar radiation, ozone concentration, or improvements in agronomic management and stress tolerance of future crop cultivars that would accompany increases in temperature (Asseng *et al.*, 2009; Cassman *et al.*, 2010). Thus, such estimates represent the impact of substantial future increase in temperature on today's cropping systems and cultivars without modification of management practices in response to changing climate. Easterling *et al.* (2007) evaluated sensitivity of maize yields to climate change by summarizing results from crop simulations in multiple locations and under different scenarios of temperature and rainfall including cases with and without adaptation of management practices to changing climate (*e.g.*, earlier or later planting date, longer or short cultivar maturity, and shifts of rainfed to irrigated systems where water supply is adequate). The study shows (i) large variability in yield response to increasing temperature, ranging from positive to negative responses for all regions, with or without farming adaptation, (ii) a consistent decrease in yield only in low-latitude environments and when simulations did not include management adaptations, and (iii) an increase in yield in mid- to high-latitude environments when simulations include management adaptations probably due to longer duration of frost-free season. Likewise, Cassman *et al.* (2010) used simulation modeling to highlight how tactical adjustments in hybrid maturity and sowing date can ameliorate climate change impact on irrigated U.S. maize. Simulated Y_P in this study ranged from 12.5 (no adaptation) to 14.7 Mg ha^{-1} (farming adaptation) under a scenario of +3ºC increase in mean temperature, representing 82 and 93% of Y_P simulated using current weather and management practices. Although previous simulation studies do not account for other 'side-effects' that may result from projected temperature increases (*e.g.*, high frequency of temperature-stress events during pollen shedding-silking window), it seems that farming adaptation coupled with continuous brute-force selection for grain yield and stress tolerance can reduce, or even eliminate, the overall effect of projected higher temperature on maize yields.

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Table 6-1. Crop-system features, production and inputs levels, and resource-use efficiency in irrigated maize (Tri-Basin NRD, Western U.S. Corn Belt), irrigated rice (Central Luzon, Philippines-dry season), dryland sunflower (Western Pampas, semiarid central Argentina), and dryland wheat (Mallee region, south-eastern Australia). Values are averages based on 2-4 years of farmer's data.

Variable	Irrigated maize in USA (*n* = 123) [a]	Irrigated rice in Philippines (*n* = 62) [b]	Rainfed sunflower in Argentina (*n* = 169) [c]	Rainfed wheat in Australia (*n* = 63) [d]
Average field size (ha)	47	2	75	80
Yield potential (Mg ha^{-1}) [e]	14.9	9.0	8.8	3.6
Actual yield (Mg ha^{-1} and % yield potential)	13.2 (89%)	6.3 (70%)	4.0 (46%)	1.8 (50%)
Total water supply (mm)	930	1657 [f]	647	225
Initial soil water (%)	25	nil	40	45
Rainfall (%)	45	3	60	55
Irrigation (%)	30	97	Nil	Nil
WP (kg ha^{-1} mm^{-1} and % attainable WP) [g]	14.0 (73%)	3.8 (32%)	6.2 (41%)	8.1 (37%)
N supply (kg N ha^{-1})				
Effective indigenous N supply [h]	145	58	92	39
Rate of N fertilizer	183	126	5	12
NUE (kg grain kg^{-1} N) and RE (kg N kg^{-1}) [i]	72 (0.43)	55 (0.37)	not calculated	not calculated
P fertilizer rate (kg P ha^{-1})	25	41	3	11
Rotation with legumes or oilseeds (% fields)	66	nil	nil	15
Conservation tillage (% fields)	78	nil	80	25
Incidence yield-reducing factors (% fields) [j]	24	nil	80	70
Chemical constraints in subsoil (% fields) [k]	nil	nil	nil	75

[a] Present study (Chapters 4 and 5); [b] Cassman *et al.* (1996) and on-farm data on water supply and phosphorous (P) fertilizer rates reported by Tabbal *et al*. (2002) for same site-years; [c] Grassini *et al.* (2009), sunflower yield potential (5.2 Mg ha^{-1}), actual yield (2.4 Mg ha^{-1}) and water productivity (WP; 3.7 kg ha^{-1} mm^{-1}) were adjusted by grain biomass oil content following Hall *et al.* (1995); [d] Sadras *et al.* (2002, 2004) and *pers. comm.*; [e] yield potential for maize and rice was simulated using Hybrid-Maize (Chapter 4) and ORYZA (Kropff *et al*., 1993) simulation models, respectively, while water-limited yield potential for sunflower and wheat was estimated from the WP functions shown in Fig. 6-2; [f] does not include water input for land preparation and initial soil water is considered negligible; [g] calculated as actual yield to water supply ratio; attainable WP for well-managed rice fields equals to 12 kg ha^{-1} mm^{-1} (Bouman and Tuong, 2001); [h] estimated from measured crop nitrogen (N) uptake in non-fertilized plots (maize and rice) or estimated as N uptake minus N fertilizer assuming fertilizer recovery efficiency (RE) equals to 0.85 (sunflower and wheat); [i] fertilizer N-use efficiency (NUE) calculated as actual yield to N fertilizer ratio while RE (shown between brackets) estimated as (crop N uptake minus effective indigenous N supply) to N fertilizer ratio (crop N uptake derived from generic relationships between grain yield and N content in aboveground dry matter as shown in Cassman *et al.*, 2002); [j] weeds, diseases, insect pests, lodging, and/or green snap (wheat data only account for root diseases); [k] alkalinity, sodicity, salinity, and/or boron toxicities.

Table 6-2. Parameters of the yield trends shown in Fig. 6-4. Relative contribution (%) of each country to maize total production is also shown.

Country/region	% total production	Period	Slope (Mg ha^{-1} yr^{-1})	r^2	Yield plateau (Mg ha^{-1})
USA [¶]	40				
Western Corn Belt					
Irrigated		1965-2008	0.13	0.90	[†]
Rainfed		1965-2008	0.08	0.59	--
Eastern Corn Belt		1965-2008	0.12	0.77	--
China	19	1965-1996	0.12	0.98	--
		1996-2008	--	--	5.0
Brazil	6	1965-1991	0.03	0.76	--
		1991-2008	0.10	0.85	--
Mexico	3	1965-2008	0.05	0.94	--
Argentina	2	1965-1995	0.08	0.83	--
		1995-2008	0.20	0.77	--
India	2	1965-2008	0.03	0.84	--
France	2	1965-1999	0.15	0.90	--
		1999-2008	--	--	8.9
Italy	1	1965-1997	0.17	0.96	--
		1997-2008	--	--	9.4

[†] Although time series did not allow identifying a yield plateau in U.S. irrigated maize, no yield increase was detected during the 2003-2008 period (average yield: 11.5 Mg ha^{-1}).
[¶] Separated yield trends are shown for states located in Western Corn Belt (Colorado, Kansas, Nebraska, North Dakota, Oklahoma, South Dakota, Texas, and Wyoming) and Eastern Corn Belt (Illinois, Indiana, Iowa, Minnesota, and Ohio). Trends for rainfed and irrigated maize are shown for the Western Corn Belt. Contribution of irrigated maize to total maize production in the Eastern Corn Belt is negligible.

Table 6-3. Estimated average changes (2046-2065 minus 1961-2000) in mean temperature (ΔT_{mean}) during current crop growing season and grain yield (Δyield) of maize in selected maize-producing countries based on outputs from 11 climate models. Numbers in parentheses are range of 11 climate models (ΔT_{mean}) and 5th and 95th percentiles (Δyield). Adapted from Lobell (2007).

Crop and country/region	% global production	ΔT_{mean} (°C)	Δyield as % of current yields [‡]
USA	40	3.0 (2.2-4.7)	-24 (-45, -12)
China	19	2.2 (1.5-3.0)	2 (-7, 8)
Brazil	6	2.0 (1.3-2.6)	-11 (-33, 7)
Mexico	3	2.2 (1.5-3.1)	-4 (-13, 5)
Argentina	2	1.9 (1.2-2.9)	-12 (-25, 2)
India	2	2.0 (1.2-3.1)	-6 (-33, 10)
France	2	2.4 (1.1-3.0)	0 (-12, 7)
Italy	1	2.7 (1.6-3.3)	-7 (-13, 0)

[‡] Estimates based on empirical relationships between national crop yields (dependant variable), T_{mean} and diurnal temperature range (independent variables).

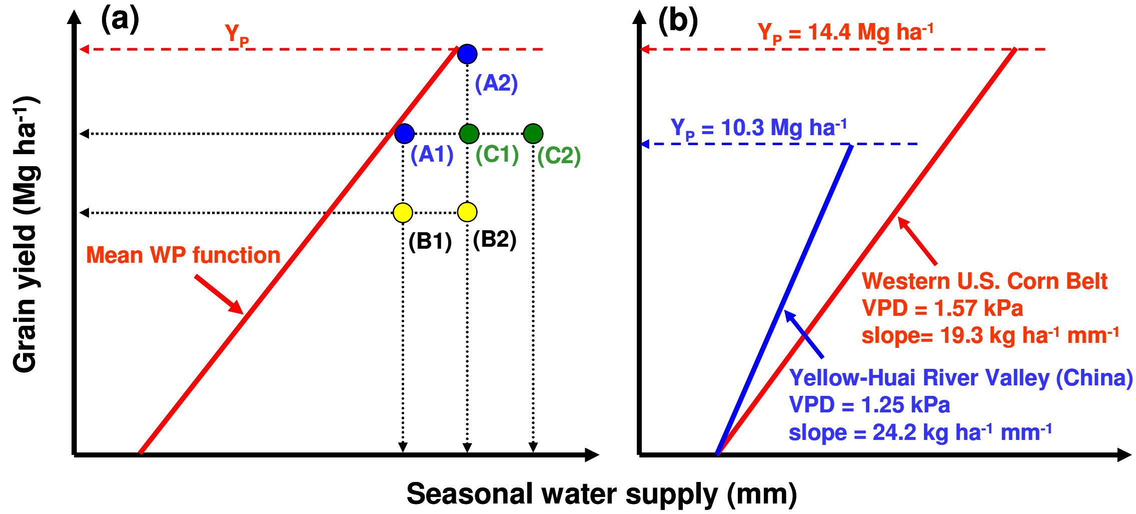

Figure 6-1. (a) Schematic representation of three farms (A, B, C) in an initial scenario (1) and when irrigation supply is increased equally to the three farms (2). Solid and dashed lines indicate water productivity (WP) benchmark and yield potential (Y_P), respectively. (b) WP benchmarks for maize in the Western Corn Belt (USA) and the Yellow-Huai River Valley (China) (red and blue lines, respectively). Parameters of the WP benchmark for China were calculated by assuming the slope of WP function to be inversely related to daytime vapor pressure deficit (VPD) while yield potential (Y_P) simulated using Hybrid Maize model in combination with actual weather and management data (Bai *et al.*, 2010).

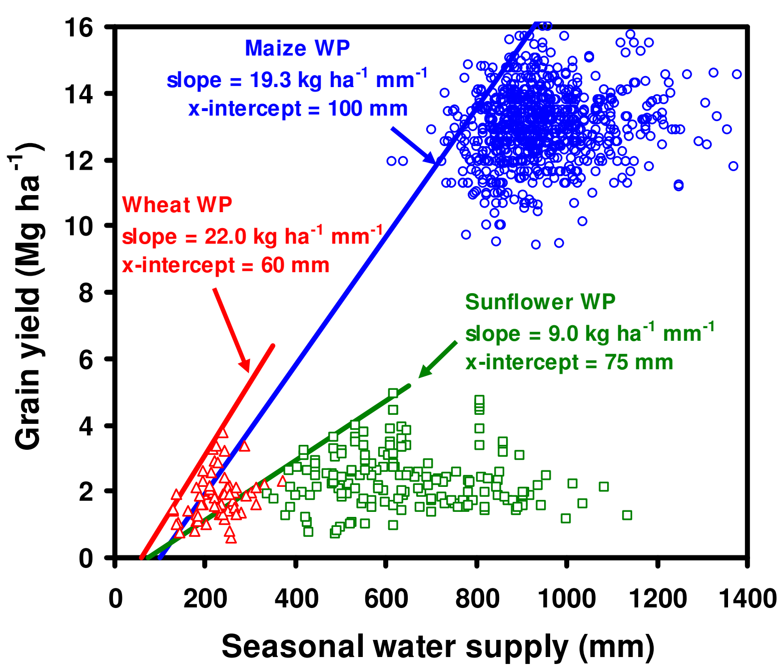

Figure 6-2. Farmer's maize (circles), sunflower (squares), and wheat yields (triangles) plotted against seasonal water supply (soil water at sowing plus rainfall and irrigation). Water productivity (WP) benchmarks for maize (present study), sunflower (Grassini *et al.*, 2009), and wheat (Sadras and Angus, 2007) are shown. Average actual yield, water supply, and WP are shown in Table 6-1.

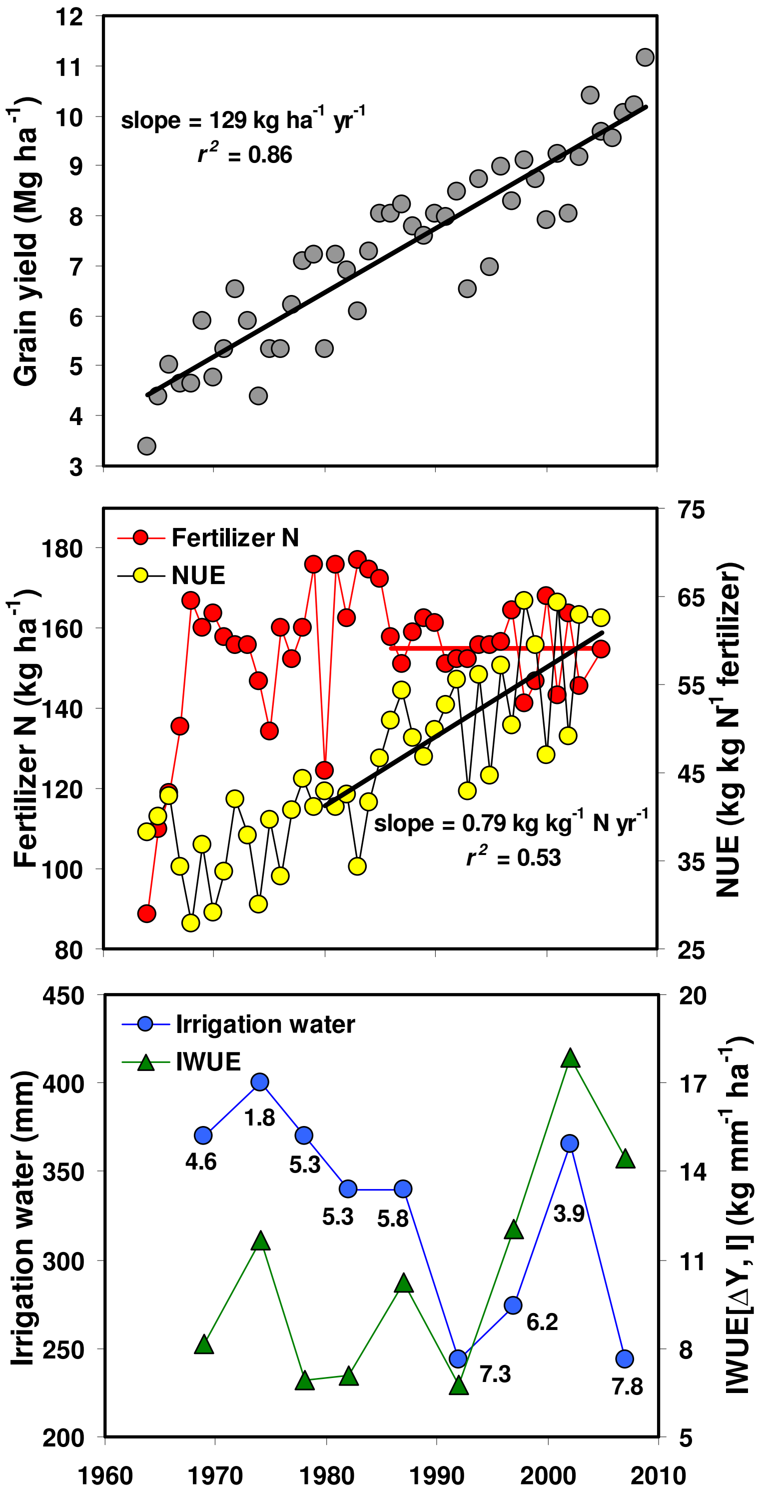

Figure 6-3. Trends in state-level maize grain yield, use of N fertilizer and irrigation water, NUE (ratio of yield to applied N fertilizer) and IWUE (ratio of irrigated minus rainfed yield to applied irrigation) in Nebraska, USA. Values in bottom panel indicate rainfed yields on each year. Data source: USDA (NASS-USDA & NASS-FRIS).

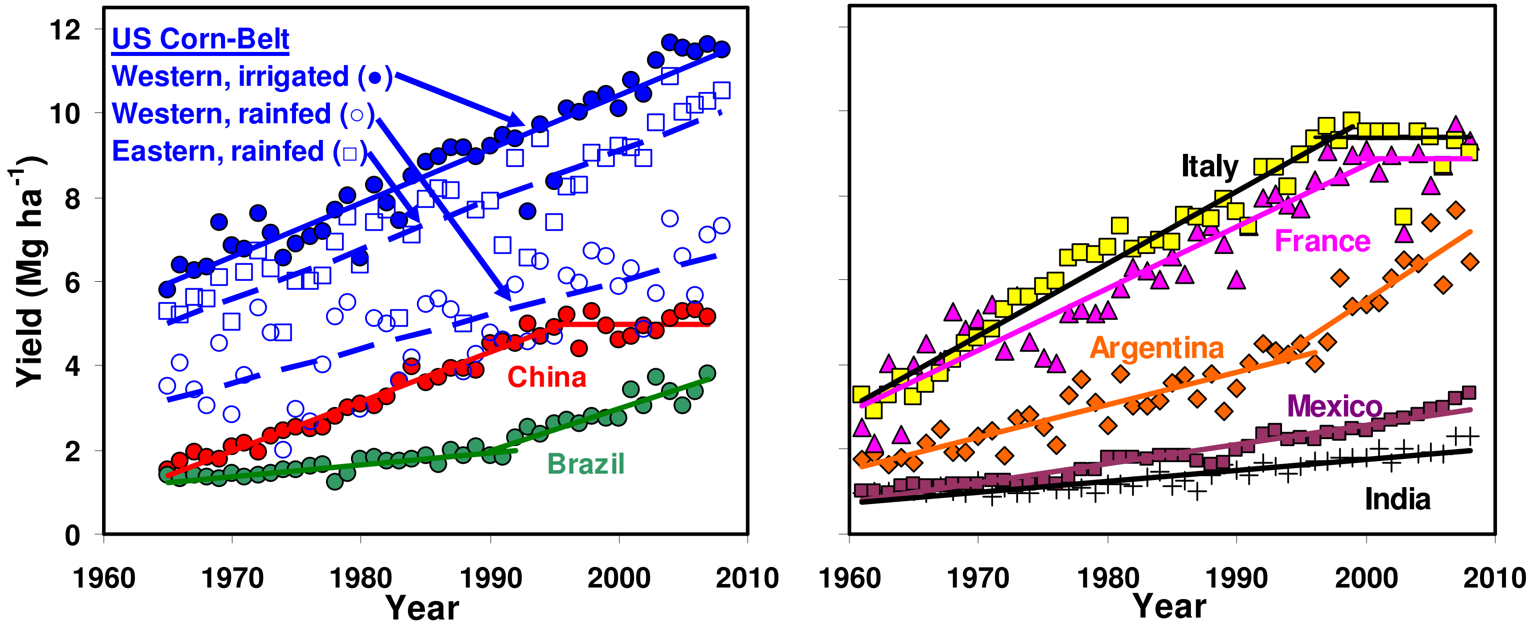

Figure 6-4. Yield trends of maize in selected maize-producing countries. These countries account for 75% of total maize production (675 MT). U.S. trend is disaggregated by region (Western and Eastern Corn Belt) and water regime (rainfed and irrigated). Irrigated maize production in Eastern Corn Belt is negligible. Western Corn Belt includes Colorado, Kansas, Nebraska, North Dakota, Oklahoma, South Dakota, Texas, and Wyoming states; Eastern Corn Belt includes Illinois, Indiana, Iowa, Minnesota, and Ohio states. Data sources: FAOSTAT and USDA-NASS.

APPENDIX

A. References that were the source of data used in Figure 2-8, which plots the relationship between aboveground biomass or grain yield versus ET_C

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